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SATELLITE DATA MANAGEMENT ALGORITHMS STUDY

Arvid G. Larson, Ph.D.
Philip H. Mason, Ph.D.
Bernhard E. Keiser, D.Sc.

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ISC PRC INFORMATION SCIENCES COMPANY
7600 Old Springhouse Road McLean, Virginia 22101 (703) 893-1800
1100 Glendon Avenue Los Angeles, California 90024 (213) 473-1163

This final report was submitted by PRC Information Sciences Company, 7600 Old Springhouse Road, McLean Virginia, 22101 under Contract F04701-76-C-0188 with Headquarters Space and Missiles Systems Organization, Advanced Concepts Division, Los Angeles Air Force Station, California, 90009. Major George A. Kuck, YAPC, was the Project Officer.

This technical report has been reviewed and is approved for publication.

George A. Kuck

GEORGE A. KUCK, Major
Project Officer

Francis J. Belmonte Jr.

FRANCIS J. BELMONTE, JR, Lt Col
Chief, Advanced Concepts Division

FOR THE COMMANDER

David B. Grover

DAVID B. GROVER, Colonel
Director of Plans

ABSTRACT

As part of an ongoing Space and Missile Systems Organization (SAMSO) research and development program into advanced space communications networks to support projected Air Force missions through the year 2000, several studies have been performed to investigate emerging issues in the design of such networks. This final report presents the results of a study to consider one specific issue -- that of the design of data management algorithms to optimize performance measures and resource allocations within network and user demand constraints. Included in this study are considerations of message distribution modes (e.g., packet switching algorithms), information control (e.g., flow control and routing algorithms) and multiple access techniques.

In the context of this study, data management algorithms consist of all the rules which govern information flow within an envisioned multiple-satellite multiple-mission space communications network. Such data management algorithms permit the orderly interaction of information sources, intelligent satellite nodes which form the communications network, and information users.

A generalized satellite-based information network model is developed in this report. Generic characteristics of the network information processing and transmission resources are identified as the basis for an evolutionary space communications network. Specific considerations for satellite data management algorithms are presented in terms of both mission-related and communications-related factors as well as relative performance measures. A comparative evaluation of data management algorithms is also given.

The final chapters of this report develop satellite network data management opportunities as well as identify specific areas requiring further technological development in the realization of an envisioned space-based information network. The concluding section presents recommendations for several study areas requiring additional investigation in support of this advanced communications network conceptual effort.

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CHAPTER I

INTRODUCTION AND BACKGROUND

A. Basic Considerations

Over the last several years, significant technical advances have occurred with respect to data communications, packet switching networks, intelligent computer terminals, distributed data processing systems, and communications satellites. As these and other relevant digital communications technologies rapidly evolve, it seems clear that current and projected state-of-the-art in these technologies now permit consideration of the logical merger of these advanced, but diverse, concepts in the development of a space communications network. Such a generalized information network could support a variety of projected Air Force missions through the next several decades and beyond the year 2000.

For example, a representative multi-mission space-based information network of this sort could employ a configuration of earth satellites to form a packet switching system for digital data transmission from any point on the earth to any other point. Each satellite would function as an intelligent node in this network, using intersatellite relay of data controlled by on-board microprocessor and data storage systems. In principal, such a packet switched space data communications network would operate in much a similar fashion to that of the current ARPANET, supporting diverse users across several distinct missions.

The potential utility of such a generalized multi-mission information network is immense. It has therefore become essential to identify the

emerging issues in the design of such a network so as to guide subsequent research and development activities to this end. One such issue is the design of data management algorithms to optimize performance measures and resource allocations within network and user demand constraints. It has been the purpose of this Satellite Data Management Algorithms Study, sponsored by the U. S. Air Force Space and Missile Systems Organization (SAMSO) under Contract F04701-76-C-0188, to perform a detailed investigation of this specific issue.

B. The Satellite Data Management Algorithms Study

In the context used herein, data management algorithms consist of all the rules which govern information flow in the envisioned satellite communications network. The objective of this study has been to evaluate the effectiveness of data management algorithms in support of specified satellite data systems missions.

Data management algorithms are necessary to permit the orderly interaction of

- Information sources
- Communications systems
- Information users

within an information network. Such algorithms include considerations for optimizing performance measures and resource allocations within network user demand constraints. An efficient allocation of network resources must additionally consider message distribution modes (e.g., packet switching), information control (e.g., flow control and routing algorithms) and multiple access techniques.

This study effort has been one of three concurrent studies sponsored by SAMSO within the FY7T period for the purpose of developing:

- User demand models
- Satellite network architecture options
- Concepts for data management algorithms

While the study results presented herein focus primarily on the third of these study areas, it is recognized that there is considerable commonalty with the first two studies, since effective data management algorithms cannot be developed without consideration for user demand models and network architectures. Thus, somewhat overlapping study efforts in these areas were also considered to be within the scope of this satellite data management algorithms study.

C. Project Methodology

This study effort has been organized to explore data management algorithms for establishing a data interconnection between multiple satellites and earth-based terminals. These efforts were conducted as part of a broader conceptual investigation into all relevant aspects of a multi-satellite multi-mission space communications system, considering the generic concept itself, the on-board satellite technology, data network methodology, and the user terminals. It has been the objective of the broader study to formulate an evolutionary set of network concepts, to identify emerging issues for efficient network design, and to project information flow options.

A four-phase approach was chosen for this investigation, consisting of:

- Development of a conceptual network design
- Forecasting of generic network requirements, such as:
  - categorization of sources and users
  - development of potential design opportunities
  - identifying inherent network characteristics and constraints.
- Enumerating critical issues with respect to:
  - mission requirements
  - data management algorithms
  - user interfaces.

- Assessing practical system prospects; for example:
  - computation requirements
  - performance evaluation
  - critical technology areas.

The results of this study effort are presented in Chapters II through V of this report. A summary of these results, as well as conclusions and recommendations, are presented in Chapter VI.

Since the selection of a basic communications network organization (i.e., dedicated channels or resource sharing, such as packet switching) is necessarily inherent to the development of data management algorithms, a review of basic communications network concepts is presented in Appendix A. In addition, an extensive set of technical literature was utilized in this work. A bibliography of relevant technical material found of value in this effort is presented in Appendix C.

D. Space Communications Missions for This Study

In order to maintain this report in the unclassified literature, specific details relative to specific projected space-related military mission requirements are not discussed herein. Moreover, these details, in themselves, are not entirely relevant to the development of basic multi-mission space communications concepts (although, as will be noted later, are essential to the consideration of data management algorithm technical detail).

A guiding document for this study has been a recent report entitled "Mission Analysis of Future Military Space Activities", SAMSO Technical Report TR-75-217(S) of December 1975 and February 1976, in which are identified a number of military space activities requiring the support of such a space communications network. Specific space missions requiring the communications support possible only from an advanced satellite communications network include:

- Surveillance satellite activities
- Meteorology satellite activities
- Remote-piloted vehicle (RPV) control satellite activities.

It is clear that the envisioned multi-mission space commnication network must support communities of disparate strategic, tactical, operations and intelligence users. For example, future space communications missions -- some of which are not entirely possible with current military communications systems capabilities -- include:

- Strategic systems
  - polar coverage
  - submarine communications
  - integration of attack warning and defense missile systems
  - object identification
  - space defense

- Tactical systems
  - links to and from maneuvering platforms (air, sea or land)
  - forward battlefield area links.

Requirements such as these then form the generic mission requirements basis for development of the satellite data management algorithms concepts discussed herein.

CHAPTER II

THE INFORMATION NETWORK

A. Introduction

An initial task in consideration of an advanced multi-mission space communications system is the development of a generalized model of such a system for the purpose of identifying basic technological considerations and alternatives in formulation of an evolutionary set of network concepts. It is felt that although this network model should be firmly based on viable technology and realistic mission requirements, and reasonable extrapolations therefrom, it can not be constrained by currently available technology. Moreover, it must be detached from programmatic limitations of current space communications projects. Rather, such a generalized network model should consider the global military data network mission requirements for the 1980 - 2000 and beyond time frame to be served by a hypothetical multi-mission space communications satellite system to form a distributed communications network in the sky.

In this target time frame, current technology will be extended by significant advances in electronic component miniaturization permitting powerful on-board satellite data processing and storage capabilities as well as data communications technology permitting sophisticated distributed processing systems utilizing advanced packet switching. Conceptually, a variety of technologies may be considered to implement the interchange and processing of information between satellite network nodes and earth-based terminals (including airborne nodes). Certain technological trends seem clear; others are emerging issues for network

design which must be identified and studied.

Similarly, a comprehensive assessment of military communication requirements through the year 2000 calls for a quantitative projection of the growth of present communications of all types, as well as the addition of new communications capabilities. An integration of all these requirements into a consolidated data communications system architecture is designated as an <u>information network</u>.*

Such a network will in general consist of a number of nodes of arbitrary interconnection. These nodes may represent one or more of three elements:

- Information Sources
- Information Relays
- Information Users

Nodes may be physically realized by earth-based elements (either stationary or mobile) or satellite-based elements.

The total data flow through the information network is then a function of how the total communication paths are proportioned between space and terrestrial nodes. For purposes of this study, it is assumed that at least one of the source, relay and/or user nodes is a satellite-based element. This assumption is based on the

- Need for information from and over hostile territory
- Need for information from and to areas in which the political environment is a difficult one

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*Note: It is recognized that there is a distinction between the use of the words <u>information</u> and <u>data</u>. This report will use the word "information" to mean both the "data" that flows in the network and the "information" that is a result of interpreting the "data". The term "data communications" is used when necessary to provide a bridge or link to identify techniques or devices that have, through common usage, come to be identified by or associated with the term.

B. Network Functionality

There are five foundation issues to be identified and resolved in the development of any generalized communication network. These issues, or mission functional considerations are:

- What is the nature of each information source?
- How are source data processed for transmission?
- How can the network resources be characterized?
- How are the data processed upon reception?
- What are each user's information needs?

The challenge to the designer of a multi-mission network is to develop common resolutions to these issues across the missions to be supported.

Certain elements relating to network functionality may be established in common across all missions. As shown in Figure II-1, one may identify three levels of network functionally:

- Correspondence between information resources and information users.
- Correspondence between connection-oriented functions.
- A broad base of communications-related functions, such as:
  - routing and switching
  - channel assignment
  - security
  - priority
  - error control
  - information delivery.

The uppermost levels of this functional organization relate more to conceptual issues concerning the interchange of information. The lower level of communications-related functions concern both conceptual approaches and the somewhat mechanical details of system implementation.

The correspondence between the information resources and information users involves the pure transfer of information, independent of the mechanism of information exchange. Alternatively, at the connection-oriented functional level, this correspondence involves the mechanism of exchange independent of information content.

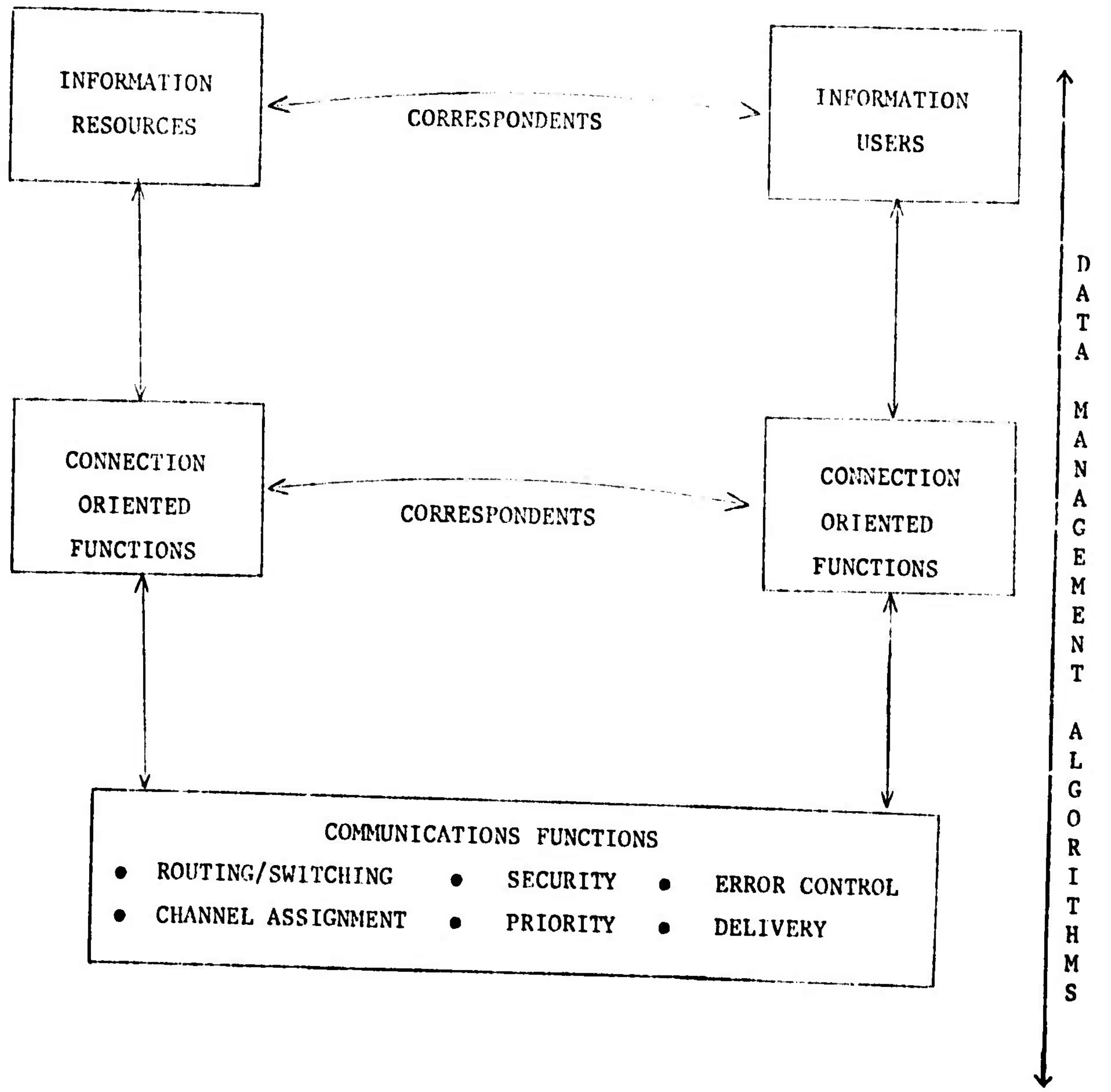


Figure II-1 -- Levels of Network Functionality

This concept is illustrated readily by consideration of a letter transmission by the postal service. The sender and the receiver of the letter are only concerned with the exchange of information. To them, the envelope to enclose the information (message), the required address on the envelope and the entire postal establishment are clearly mechanistic detail relative to a specific system implementation. Their correspondence is at the information exchange level, independent of the mechanism of information exchange. On the other hand, the address on the envelope is a connection-oriented function used only to designate the proper sender and receiver, independent of information content. The envelope, postal stamps, mailboxes, and necessary operation of the postal service are purely communications-oriented functions, and of course completely independent of the information being transmitted.

It may be noted in Figure II-1 that data management algorithms necessarily span all three levels. Although connection-oriented functions most strongly influence the selection and design of data management algorithms, it is stressed that the other two levels are also a necessary and important basis to the development of <u>any</u> data management algorithm.

C. <u>A Generalized Model</u>

The fundamental organization for information exchange between sources and users is the information network. As shown in Figure II-2, the network consists of three discrete elements:

- Sources
- Relays
- Users.

Sources and users are interconnected through relays over <u>interlinks</u>.

A simplified illustration of the general information network model is given in Figure II-3. It illustrates the sequence of information flow between a single source of desired information, <u>S</u>, and the single user of the information, <u>U</u>. At least one relay, <u>R</u>, may exist in the information flow between the source and the user. It is noted that an interactive

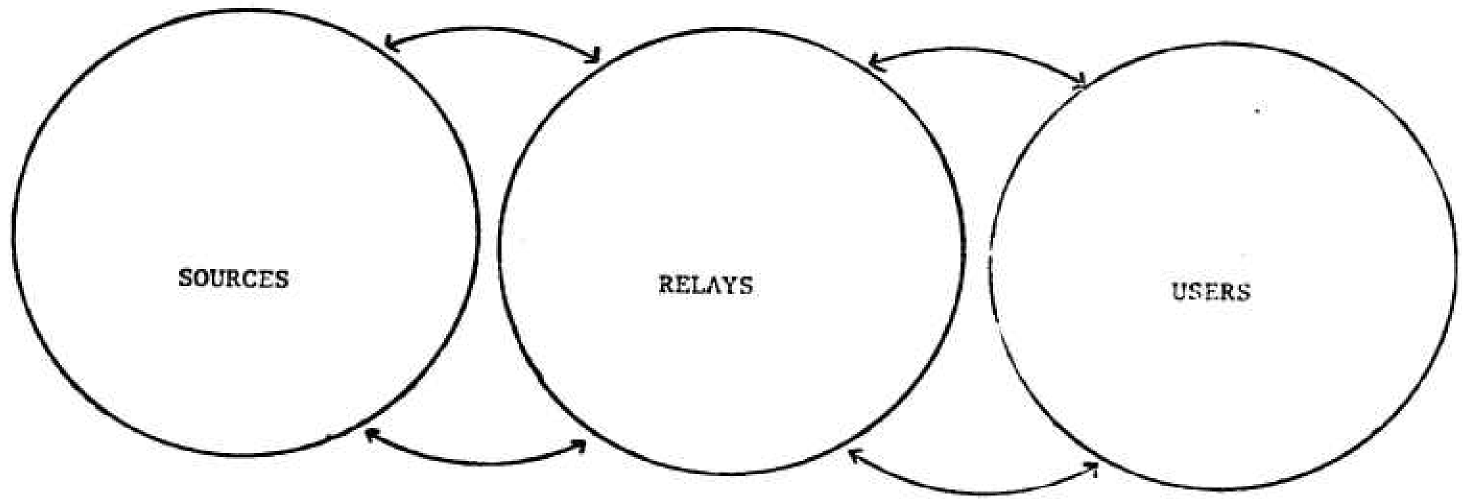


Figure II-2 -- Elements of an Information Network

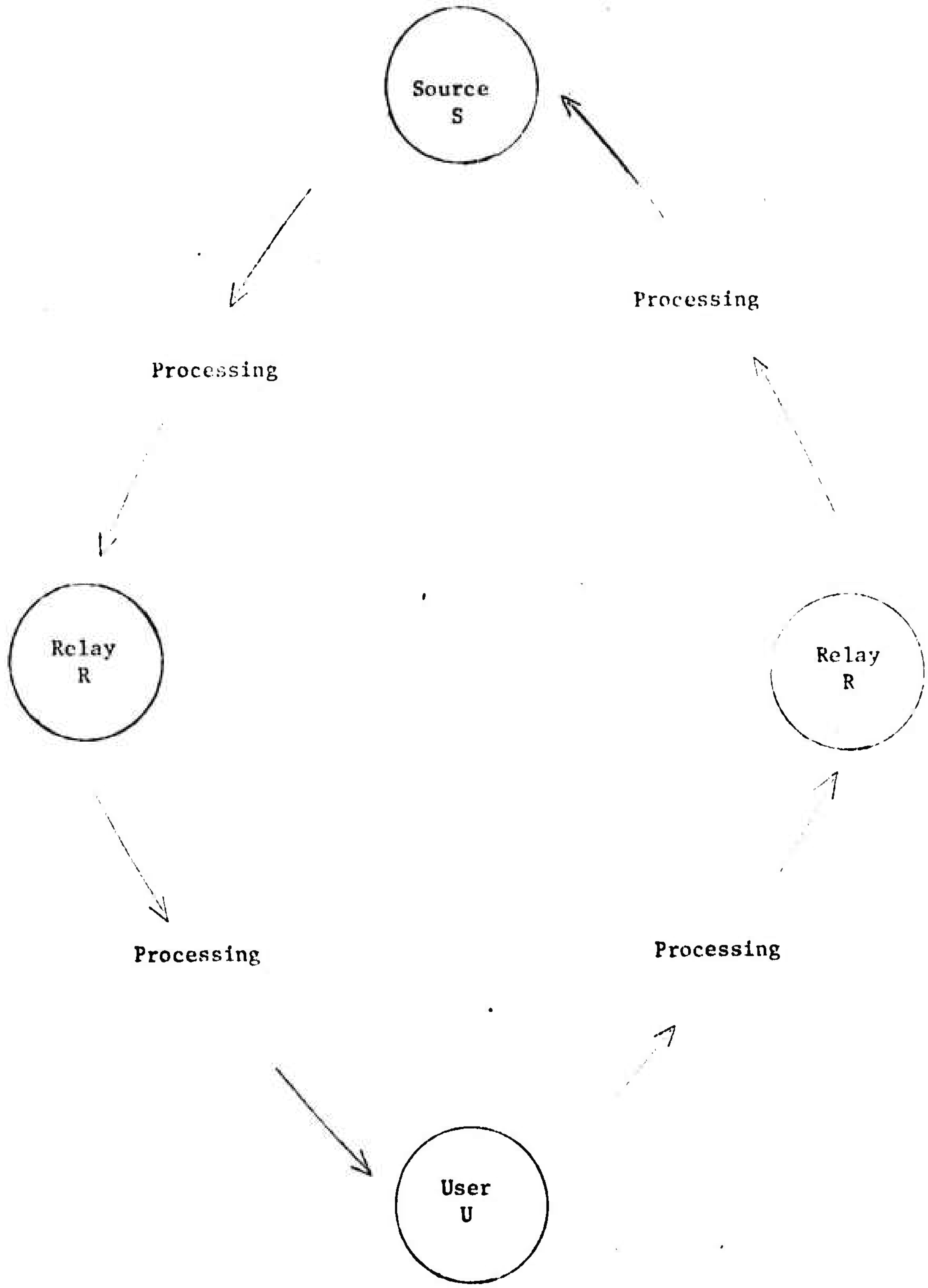


Figure II-3 -- Simplified Information Network Model

cyclic information flow is visualized, such as a command from the user to the source, resulting in a set of data from the source to the user. Moreover, processing of any portion of this information flow may occur at any location in the information network. In general, such processing is colocated within a source, relay or user. Additionally, any set of source, relay(s), and/or user may be colocated.

The general information network actually consists of an arbitrary number of sources, relays and users, interlinked in a totally general fashion. Such a model is shown in Figure II-4. No constraint need to placed on the physical location of any source, relay(s) or node (i.e., terrestrial-based or satellite-based). It is important to note that one user of information may be a source or relay of other information, etc. In any interactive operation, the functional roles of source and use of information reverse between the command and data flow sequence.

The information processing functions may occur at any point in the information flow sequence. It is obvious that, in general, any desired processing may be accomplished at any node between (and including) a source and a user, subject only to pragmatic constraints. Such processing, including information selection, compression, transformation, fusion and storage, may thus occur at or among any of the total path nodes. By arguments of functional transposition, all desired processing may be located within one node, or distributed among any of the nodes. In practice, this latter case is by far the more common.

Although the general model shows separate interlinks between source and user and between user and source, only one of these interlinks need actually exist. If both do exist, they may be colinear, sharing a common communications path. A generalization of all possible interlink distribution modes would include:

- Broadcast (point-to-multipoint)
  - Real-time Broadcast
  - Store and Forward

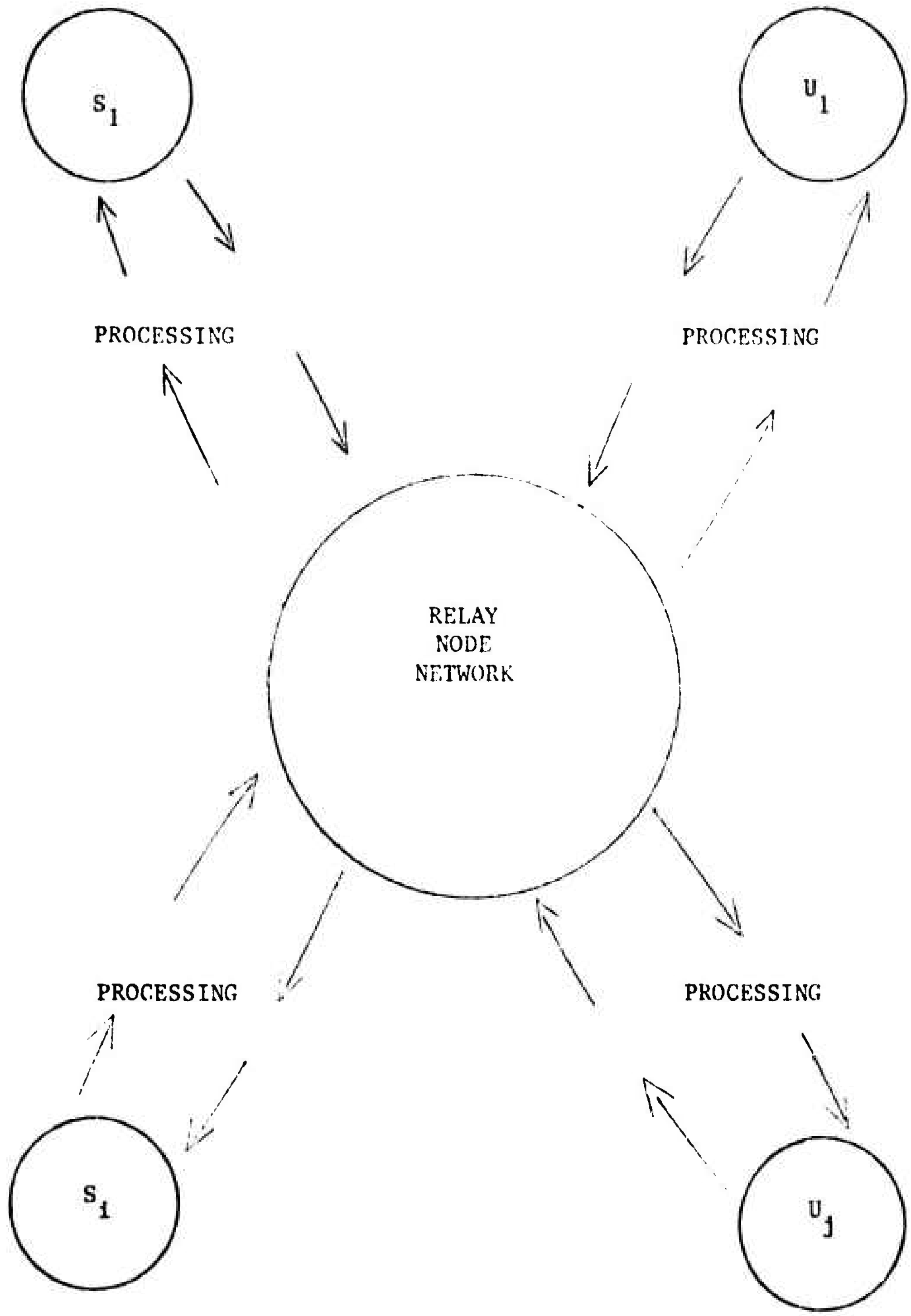


Figure II-4 -- Interconnection of Sources and Users

- Point-to-Point (among Nodes A and B)
  - Store and Forward
  - Unidirectional (node A to Node B)
  - Bidirectional
    - -- Half Duplex
    - -- Full Duplex
  - Unidirectional (Node B to Node A)
  - Polling
- Gathered (Multipoint-to-point)
  - Polling
  - Multi-source Acquisition

Such a set of generalized information network interlink distribution modes is illustrated in Figure II-5, along with typical examples of each use.

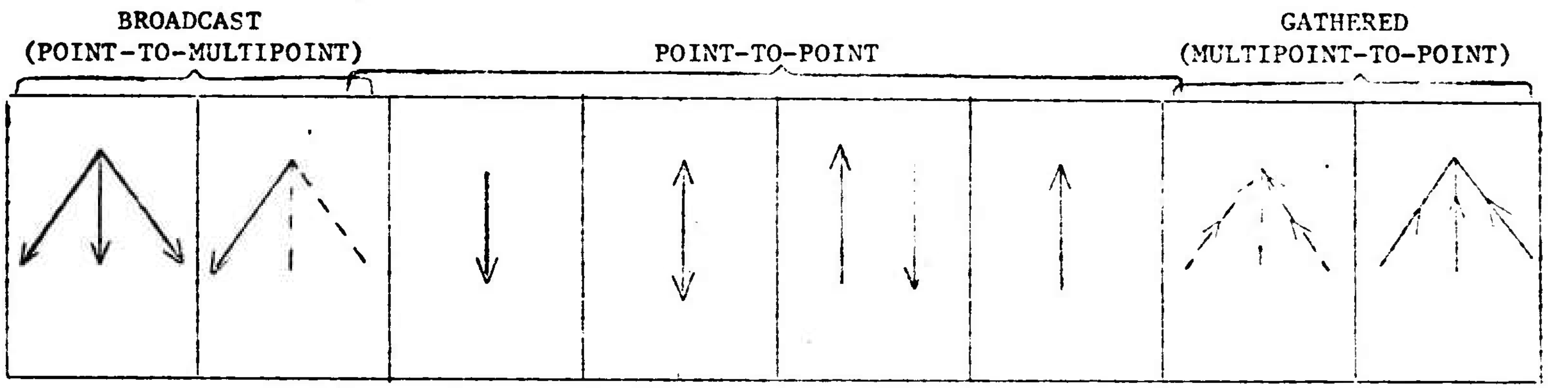
An important characterisitic of this information network model is the inherent multiplicity of interlinks between a given source and a given user. A network of relay nodes, generally interconnected, provides parallel and redundant information flow paths between any source and user via one or more intermediary relay nodes.

It is this availability of parallel interlinks between communicating sources and users that provides the opportunity for flexible network routing. A variable routing scheme is thus most appropriate for this model in that it would support parallel transmission of individual portions of an information transfer, be it commands or data. Such information transfers portions, or packets, may be arbitrarily sent through the network in any sequence from sender to receiver. Permitting intelligent switching at each element then forms the basis for a packet switched information network.

D. Key Features of the Model

The generalized information network model contains many features of significance to the envisioned multi-mission space communications network. Principal key features of this network model are:

- The network is entirely information exchange independent.
- There is no constraint on node location and/or operation (e.g., earth-based, air, satellite, manned, unmanned, etc.)
- Network sources and users may alternate roles.



Real-Time Broadcast	Store and Forward	Unidirectional	BIDIRECTIONAL Half-Duplex	BIDIRECTIONAL Full Duplex	Unidirectional	Polling	Multi-Source Acquisition
EXAMPLES							
Conventional Message Communication Links		Command Link	Simple Telegraph Circuit	Telephone Circuit	Surveillance Sensor Links	Status Monitoring Links	Multi-Source Surveillance Links

Figure II-5 -- Information Network Interlink Distribution Modes

- Any set of source, relay(s) and/or user may be collocated
- Information processing may be distributed through network or centralized at any node
- There is a multiplicity of separate interlinks between each source and user pair.

Each of these features relate to a desired quality of an evolutionary information network. A detailed consideration of this model thus provides a set of generic network characteristics, as another mechanism for for defining necessary network attributes in a multi-dimensional descriptor space.

E. Generic Characteristics of the Network

A general schema for generic classification of the network model is presented in this section. It is based on two independent sets of characteristics, namely:

- Information-related characterisitcs
  - information-use
  - information-flow
- Node-related characteristics.

The application of these generic attributes within the general model permits focusing upon potential future opportunities in a general interactive information network. This analysis will, in turn, identify critical issues which may be then tested against technical details, such as:

- Information quantity
- Information transmission rate
- Geographical distribution of sources and users
- System constraints

Each set of generic characterisitcs of the general information network may be defined in a multi-dimensional descriptor space. A useful enumeration of bounding characterisitcs of this descriptor space is contained in Tables I through III, along with illustrative examples of their application. It is recognized that this descriptor space as presented is neither distinct nor exhaustive, but it is felt to provide adequate insight upon which to base potential network development opportunities.

TABLE I

INFORMATION - USE ATTRIBUTES

CHARACTERISTIC	EXAMPLE
A. Information Availability	
• Continuous	Surveillance Satellite
• Periodic	Meteorological Satellite
• Infrequent (Bursty)	C^2 Mission
B. Information Application	
• Operational	
- Command and Control	Force Status
- Navigational	Navigational Satellite
- Meteorological	Weather Forecasting
• Intelligence	
- Basic	
- Tactical	
- Strategic	
• Administrative	Personnel Action
• Archival	Remote Data Base
C. Fusion	
• Multi-Source	Surveillance and ELINT
• None Required	Command Acknowledge
D. Routing/Distribution	
• Broadcast	Navsat
• Point-to-Point	RPV Control
• Gathered	Command Center

TABLE II

INFORMATION - FLOW ATTRIBUTES

CHARACTERISTIC	EXAMPLE
A. Information Priority	
• Dominant (Highest)	Flash
• Inherent Relative	Routine, etc.
• None	Administrative Actions
B. Information Control	
• Highly Sensitive	Eyes only, codeword
• Limited Distribution	TS, Secret, etc.
• Unlimited Distribution	Broadcast
C. Information Timeliness	
• Real-Time/Near-Real-Time	Voice, Tactical Intelligence
• Medium-Long Term	Strategic Intelligence
• Archival/Non-Time-Sensitive	Personnel Records

TABLE III

NODE-RELATED CHARACTERISTICS

CHARACTERISTIC	EXAMPLE
A. Node Function	
• Information Source	RPV Sensor Platform
• Information Relay	Control Satellite
• Information User	Tactical Commander
B. Node Location	
• Fixed (Land-Based)	Command Center
• Mobile	
– Low-Speed	Man, Tank, Ship
– High-Speed	Aircraft, Missile
• Satellite	
– Near-Earth Orbit	LANDSAT Platform
– Geostationary	Broadcast Satellite
– Cislunar and Beyond	?
C. Assumed Threat Environment	
• Active Threat Possible	
– Physical Threat	Attack, Bombing
– Electronic Threat	Jamming, Spoofing
• Passive Threat Possible	
– Physical Threat	Surveillance
– Electronic Threat	Network Penetration
• Benign Environment	COMSAT, ARPANET

F. Network Resources

The general information network model provides two fundamental network resources. These are the:

- Transmission of information (between source and user); for example:
  - interchange
  - switching
  - route selection
  - storage
- Processing of information; for example:
  - selection
  - compression
  - transformation
  - fusion
  - storage.

The overall satellite data management consideration is the effective utilization of these resources in an evolutionary satellite communications network. It is the role of data management algorithms to provide the flexible utilization of these resources within the constraints of technical detail imposed by communications-related functional requirements.

CHAPTER III

AN EVOLUTIONARY COMMUNICATIONS NETWORK

A. Introduction

A basic premise of the satellite data management program is that a multi-mission space communications system can enhance the utility of data flow via multi-satellite relay between information sources and information users. This can be accomplished within such an envisioned system if provisions for effective sharing of transmission and processing resources within the communications network are provided.

The design of the envisioned space communications capability must support an evolutionary developmental sequence. The specifics of the sequence itself are not particularly germane. However, for purposes of illustration, one envisioned network development sequence could be:

(1) Install a simple switching element, including on-board data processing and storage, in a single satellite to support one generic program, say space surveillance [illegible] a defined community of users.

(2) Using several interlinked identical intelligent satellites, implement a simple multi-satellite communications network to support two or more missions with partial global coverage.

(3) Form a distributed space communications system using 5-10 intelligent satellites of varying technological capability, in a hierarchical network organization using packet switched data transmissions with full global coverage for complete communications and processing support of several relatively disparate missions (e.g., meteorological missions and RPV missions).

A host of data management issues readily emerge from a consideration of such an evolutionary communications network. Data management algorithms necessary to permit the effective sharing of processing and transmission resources are an intrinsic part of these issues. At a minimum, evolutionary data management algorithms must be developed to support:

- Information Flow Control
  - Channel Assignment
  - Dynamic Routing
  - Distributed Resource Management
- Information Transformation
  - Data Compression
  - Multi-Source Fusion
  - Pre/Post-Processing
- Adaptive User Feedback
- Error Detection and Correction
- Information Security/Priority Considerations
- Spoofing/Jamming/Penetration Considerations
- Performance/Resource Optimization

These considerations are further developed in this and subsequent chapters of this report.

B. Generic Data Management Requirements

The development of evolutionary data management design alternatives requires a general quantification of overall data management requirements for each space-related mission to be supported. A generic classification may be established in terms of representative military space missions to provide relative system performance requirements such as

- Information volume
- Time between transmissions
- Tolerable connect delay
- Tolerable transmission delay

The diverse, but strongly representative, military space missions relating to surveillance, meteorology and RPV have been chosen for this purpose.

Overall data management requirements form the basis for selection of the proper communications network to support individual military missions or multiple military missions. It is thus useful to categorize these missions in terms of communication system performance characteristics. Table IV summarizes such a characterization, indicating relative communication system requirements for each of the three representative missions. Several clarifying comments should be made.

Surveillance missions usually deal with large volumes of information such as pictures and electronic or other emissions. It is often necessary that this information be sent in total to a ground processing station for distribution and exploitation. This may not be necessary in all cases if some processing is performed in the network, for example, if only current status or status changes are reported. If this were done, then actual data transmission requirements could be moderate or low volume. In either case, the frequency of information occurrence from a single sensor is relatively low or at most moderate. Since from a systems viewpoint there may be many sensors operating simultaneously, the communications network could be required to handle information at moderate to high rates of occurrence. The communication network connect time and transmission delays for routine surveillance could tolerate a moderate connect time delay. However, during crisis situations, this information should be available with absolute minimum delay. The communications network must then be designed to handle both requirements.

The meteorology mission is, in many ways, similar to the surveillance mission in terms of its information communications requirements. The major difference is in the tolerable time delays for network connection and transmission. It is not typical that the meteorological communication network support real or near-real-time communication; accordingly moderate delays should not be critical.

In contrast, the RPV mission requires real-time or near-real-time interactive operation, thus connect and transmission time delays must be

TABLE IV

SELECTED MISSION ORIENTED PERFORMANCE REQUIREMENTS

Mission	Surveillance	Meteorology	RPV
Information Volume	High and Low	High and Low	High and Low
Time Between Transmissions	Low	Low	Low and High
Connect Delay Tolerated	Moderate; Low and High	Moderate	Absolute Minimum
Transmission Delay Tolerated	Moderate; Low and High	Moderate	Lowest

minimal for most RPV missions. The information traffic will probably occur with high volume and frequency from the remote vehicle to its controller with low volume and frequency in the other direction. For example, the vehicle will probably transmit status and sensor-derived information (including pictures), whereas the controller will probably transmit commands intermittently as they are needed.

A satellite communications system designed to foster substantial resource sharing and to simultaneously support each of these three missions obviously requires broad capabilities to accomodate such diverse performance goals. Some commonality may be noted, but it is most clear that a general multi-mission communications capability must support a broad variety of performance characteristics in every quantitative dimension. Such then is the challenge offered to the designer of such a system. However, it is also believed that current network control and network routing techniques, such as are employed in the ARPANET and other ground-based multiple-user digital data communications systems, offer significant opportunity to meet this challenge.

C. Evolutionary Network Characteristics

The envisioned space communications network must be based on an evolutionary set of operational capabilities. Conceptual evolutionary network characteristics may be specified in terms of:

- Network control
- Network routing

A brief discussion of each generic characteristic is presented herein.

1. Evolutionary Network Control

The three network supervisory control alternatives to support resource sharing and evolutionary growth are centralized, distributed, and hierarchical.

a. Centralized Supervisory Control

A single, centrally located supervisory control node usually suffices for small to medium sized networks in which message delay is small, or in which longer delays are tolerable. Such control is achieved by one or more terminals that can act as source and/or user nodes.

Large centrally controlled networks may require two or more control nodes because of the volume and frequency with which the control functions must be performed. Such nodes, as a group, make up the network control location. For example, one node may be used to enter control messages while another, often a receive-only device, is used to maintain the log of the network's control activities.

b. Distributed Supervisory Control

Relatively large networks with multiple network processors may operate with shorter queues and better cost effectiveness by using some form of distributed supervisory control. Control locations may be selected on a regional or area basis or may be those locations where network processors have been placed.

Each supervisory control location requires the logic necessary to handle the control messages it receives. Logging of the control message activity may be held in a queue and periodically sent to a node equipped with a logging device.

Two types of control messages are encountered in distributed supervisory control: those that are entered from a source/user node serviced by the network processor and those that are entered from an adjacent control node.

c. Hierarchical Supervisory Control

In large networks with distributed supervisory requirements, a method of controlling the entry of supervisory messages may be needed. This is especially true of a multi-mission military satellite system. In that event, the supervisory control function can be organized into three hierarchical levels: terminal, intermediate and master.

(1) Terminal Supervisory Control

This level includes such functions as requests for retransmission of a lost or destroyed message, and other similar node-oriented activities.

In networks with various classes of nodes or levels of security, it may be necessary to identify subsets of the node control functions and only accept control messages within the subset to which a specific node is assigned.

(2) Intermediate Supervisory Control

This level includes those control functions that are limited to supervisory control nodes, and cannot be initiated from other nodes. Adding or deleting nodes or interlinks to the software tables representing the network configuration, requesting a statistical information report, changing routing, and altering poll/select sequences are examples of intermediate supervisory control functions. Such control messages are entered from such nodes that have been identified as "supervisory control".

The set of functions that can be initiated by intermediate supervisory control nodes usually, but not necessarily, includes the lower terminal control functions as a subset.

(3) Master Supervisory Control

This level of supervisory control includes all lower level functions plus the ability to initiate actions reserved exclusively for the designated master control node. The master control node is usually located in some central facility.

The terminal complement for the master supervisory control function in large networks usually consists of several devices: one or more receive-only devices for activity logs and statistical reports, an active master device for entering control messages, and one or more standby or backup devices for use in the event of failure.

Control functions usually reserved for the master location include the changing of security level information in routing tables and other sensitive activities whose initiation should not be possible by any intermediate or terminal level messages.

Large networks may require a logical subsetting of the supervisory control functions based upon mission, regional, or

some other organizational boundaries. Those networks shared by entirely separate missions have a similar subsetting requirement. A comparable problem is presented by a cluster of nodes unique to a specific mission requiring supervisory control functions unlike any others in the network.

2. Evolutionary Networking Routing

The four most common network routing alternatives are:

- Dedicated channels
- Circuit switching
- Message switching
- Packet switching

The first three approaches are characteristic of the bulk of all current military information transmission networks, whether satellite or ground-based interlinks are used. In general, they are not entirely suitable to support future digital data transmission requirements. This is principally due to the bursty nature of data transmission, occurring essentially randomly as a function of time, where source and user node locations may also vary with time.

A detailed discussion of the specific attributes and a relative comparison among the four routing alternatives are given in Appendix A. In summary, both the message switching and the packet switching approaches appear to be very useful ones for a multi-mission military satellite system. Both offer the inherent flexibility and extensibility necessary for an evolutionary multi-satellite system development.

The message switching and the packet switching approaches are forms of distributed store-and-forward switching, permitting elimination of the long "connect time" delay inherent in circuit switching, thus providing greater responsiveness. The path any given information quantum follows is not determined in advance, as is the case with conventional circuit switching. Instead, the optimum routing is determined for each quantum as it passes from node to node, taking into account processor and circuit loading and any outages. High overall network reliability and use is thus achieved.

As is developed in Appendix A, distributed store-and-forward packet switching is a natural choice for a multi-mission evolutionary communications network. The inherent nature of a packet-switched system in which messages are broken up into sets of packets, with each packet making its way independently through the network to its destination, permits most effective processing and transmission resource sharing.

Control of the system is also inherently distributed throughout the network, with each node providing routing and flow control on the basis of its current knowledge of the network status. In general, packet switching permits simultaneous sharing of wideband transmission facilities by a number of users, and is relatively mission independent, thus creating a high-capacity and quite economical communications medium.

D. Discussion

An evolutionary multi-mission space communications system seems technologically feasible based on currently available computer, communications and satellite technology and reasonable extrapolations thereof. It seems likely that the actual implementation of such a multi-satellite information network will be necessarily evolutionary, with successive generations of increasingly technologically sophisticated intelligent satellites being added to the system over a period of time. A fundamental issue then in the selection of required satellite data management algorithms is the availability of a given algorithms set to support the necessary expansion and system extensibility implicit in the conceptual evolution of the system capability.

Information flow control seems the most critical consideration. Several natural selections occur that tend to best support all multi-mission and evolutionary growth objectives. A distributed supervisory network control algorithm best provides necessary decentralized control and flexibility in the network operation. Similarily, a variable routing control algorithm, based on packet switching techniqués, best provides accomodation of the many disparate requirements of information volume, transmission rate, tolerable connect time and transmission delay of the several representative military communications to be supported. Packet

switching does permit efficient accomodation of both short and long messages of various information content priorities with minimum delay. It also permits efficient accomodation of variable message rates, varying from near-continuous to very intermittent, on a single channel. Most importantly, assuming the availability of parallel interlinks, packet switching best supports effective sharing of network transmission and processing resources, thereby providing appreciable reductions in transmission delays as well. Distributed packet switching control is readily extensible for support of evolutionary networks growth and communications capability.

A number of specific technical considerations for satellite data management algorithms are developed in the following chapter of this report. It is necessary to also consider constraints imposed on the evolutionary development of the envisioned network by the selection of an algorithm set. For example, consider that the space communications network will eventually employ both geosynchronous and near-earth-orbit satellites. Further suppose that in support of a specific mission, communications must occur between an information source and an information user via a relay satellite with relative motion (i.e., through a near-earth-orbit relay satellite). This might happen when information exchange occurs between a polar region and the opposite hemisphere. Assuming that it is possible for the moving satellite to be properly tracked by the source and user nodes, there is still a problem: what happens when the moving satellite goes out of the range of one of the stationary communicators. The obvious solution is to "hand over" the communication to the next moving satellite. Different data management algorithms approach this problem differently, not all consistent with network evolutionary growth objectives.

Using dedicated channels, an easy solution is to have all relay satellites dedicated to the same communication path. When a satellite is not within view of a source, geosynchronous relay or user node, it is not used. This is obviously an expensive solution.

For circuit switching and message switching routing algorithms, the problem may be severe. Since there can be no upper limit on message size for either algorithm, it must be conceptually possible to "hand over" the transmission to another relay in the middle of a message communication. The not too attractive alternative is to dynamically break off transmission and resend the complete communication. This alternative for either case means that such relay satellites must have sufficient processing capability to recognize that a "hand over" can occur and to know when it is coming. Such problems multiply when it is recognized that on-board processing and storage capacity of each relay satellite must be available for all possible "hand overs", total capacity being highly dependent on the number of relay satellites within the network.

Utilizing packet switching algorithms, the problem can be accomodated relatively easily. Since all information exchanges occur through packets, only one small packet need be involved in the "hand over". The simplest solution is to resend any packets that are lost during a "hand over". It is not necessary to keep track of current communication paths since they are determined dynamically for each packet. Any number of synchronous or near-earth-orbit relay satellites may be added to the network without the need to increase the on-board processing or storage resources of existing network satellites. Thus evolutionary development can be accomplished utilizing various mixes of existing network resources and technologically improved additions at lowest cost.

CHAPTER IV

CONSIDERATIONS FOR SATELLITE DATA MANAGEMENT ALGORITHMS

A. Introduction

Satellite data management algorithms must permit optimization of performance measures and resource allocations within network and user demand constraints. From a network control point of view, these disparate constraints imposed on the envisioned evolutionary multi-mission space communications system strongly support the selection of a form of distributed supervisory control. In addition, it is clear that a general priority scheme must be adapted such that urgent messages can pass unhindered by network blockage from low priority messages. However, further development of specific data management algorithms design requires careful consideration of several mission and system related performance characteristics.

The previous discussion of generic characteristics of representative military missions suggests that the simultaneous accomodation of these characteristics within a single space communications system requires the attainment of diverse design goals. This is because individual mission-related characteristics tend to optimize different communication traffic requirements and communication system uses. These characteristics fall into categories related to the system requirements for the missions supported and into categories that relate more closely to the system's physical limitations and design considerations. These two categories have been designated as Mission Factors and Design Factors:

- The Mission Factors are those that describe characteristics of the information that passes through the communication sys-

tem. The characterization is description rather than meaning. For example, the characterization can account for 10000 bits transmitted, but cannot describe that a picture is transmitted.

- The Design Factors are those that describe characteristics of the communication satellite system. These characterizations refer to system functional requirements and capabilities. For example, resource sharing is a system property rather than an information communication property.

In this chapter, various necessary considerations for satellite data management algorithms are discussed with respect to:

- Mission-related considerations
- Communications-related considerations
- Performance measures

The concluding sections present comparative evaluations of data management algorithms with respect to these considerations to guide the network control algerithm design within the envisioned space communications system.

B. Mission-Related Considerations

For each of the military missions to be supported, important data management algorithm considerations involve:

- Information-related factors
  - Information unit size
  - Information rate of occurrence
- Network-related factors
  - Transmission time
  - Connect delay time

A discussion of each topic follows.

1. Information Unit Size

It is well established in information theory that a physical measure of information may be described in terms of bits. It is obvious, of course, that it is possible to convert analog information to digital representation and vice versa. For example, in telephone networks this

transformation is performed by the use of a device called a modem (modulator/demodulator). The size of information units for representative military missions can range from one bit to an infinite number of bits. Communication of an infinite number of bits will be designated as continuous communication.

Data management algorithms differ in their ability to handle different sized information units. Both dedicated and circuit switch communication techniques can handle all information sizes equally well. This is because once a communication path is established, the limits to information exchange are physical characteristics. These limitations include such factors as bandwidth and transmission delay.

Message switched algorithms can accomodate a variety of message sizes. For very small messages, a significant amount of overhead is required per message to carry extra information, such as the message sender, destination, and its priority. For messages that are sufficiently large this overhead becomes negligible, but other problems emerge. For moderate sized messages, each network relay node introduces transmission delays that are associated with bandwidth and message size. For large messages, since the entire transmission must be received at each node before it can be retransmitted to the next node, significant delays may occur at each node along the communication path. The net effect is a large and possibly intolerable delay at the destination. Furthermore, if there are any errors encountered that require message retransmission, the entire message must be resent. An alternative usually used is some form of error correcting overhead added to each message. This then also delays message transmission by increasing message size.

Packet switched data management algorithms provide substantial advantage over message switched techniques. Like the message switched algorithms, in packet switched algorithms individual messages that are less than the maximum packet size are handled inefficiently. However for messages that are large, packet switching offers potential benefits that may even be better than dedicated lines and circuit switching. Since large messages are broken into packets, each packet can be retransmitted

upon receipt. Thus packet switching does not suffer from the delay introduced by waiting for the entire message to be transmitted. Furthermore, packets may take independent paths from source to destination. When there are parallel paths, they may all be used simultaneously to achieve a bandwidth larger than a single path. Packet switching has been demonstrated for continuous voice transmissions (it is found that ignoring messages received out of sequence presents little difficulty in speech understanding). It seems reasonable to anticipate that packet switching can handle other types of continuous transmissions.

In summary, dedicated lines and circuit switch technique do well on all sized information units. Message switching performs poorly on small and large sized information units. Packet switching performs relatively poorly on small messages, very well on large size messages, and efficiently accomodates mixed-size messages.

2. Information Rate of Occurrence

In this discussion, the term information rate of occurrence refers to how often an information unit is transmitted. The rate of occurrence is not necessarily independent of the information unit size, and an interrelationship may exist. On one extreme, there may be a large amount of time between transmissions (hours, days, weeks, etc.); on the other extreme, the time between successive transmissions may be minimal. This latter situation also is called a continuous transmission since it is not very relevant from a network point of view whether the transmission is one long information unit or many short information units. The time between transmissions is a common communications system descriptor and a large amount of statistical study has been developed in this area. The descriptions of message events may be uniform (i.e., periodic transmission intervals), exponential, Guassian, random, or other appropriate statistical distributions. In development of alternative data management algorithms, the mean time between transmissions is found of more utility than the particular statistical distribution of the information rate of occurrence.

For dedicated lines and circuit switched approaches, the time between transmissions is not important for information exchange purposes. When the average time between transmissions is large, the network communication resources are unused and therefore wasted. As a result, these approaches are inefficient when there is a large amount of time between transmissions (note "large" is relative to the size of the information unit).

Message switched algorithms are predicated on sharing communication resources. This approach works best when the average time between successive information unit transmissions for each message sender is large relative to the entire set of message senders. The overall information throughput as well as the efficiency of network resource utilization increase with the number of messages passing within the network. However, the delays encountered for transmitting each message are directly related to the message traffic. Message switched algorithms can be efficient in the use of communication resources, but may cause large delays when there are many messages in the system. In addition, the relative sizes of the messages can also affect how well the message switched approach can accommocate mixed size information units since a few frequent large messages can delay all messages through the system.

Packet switched-based systems follow similar design goals to message switched-based systems. However, packet switched algorithms handle "bursty" transmissions well. In addition, since messages are broken up into packets, large messages may be interlaced with small messages and typically do not interfere to any extent.

In summary, both dedicated and circuit switched data management algorithms handle all rates of information occurrence well, but are inefficient when the time between transmissions is large. Message switched algorithms expect the time between transmissions to be large and do not provide efficient nor effective service otherwise. In addition, large information units

can have a detrimental effect on the overall network performance, especially if they are frequent. Packet switched algorithms also perform best for infrequent transmissions from single users, but in general packet switched system performance is not impacted as severely with large, frequent information units as are message switched algorithms.

3. Transmission Time

Transmission time is that time required to send one unit of information between an information source and an information user. At the minimum this time is proportional to the physical distance traveled by the information. Other factors contributing to this time are the interlink bandwidth available for the transmission, the selected data management algorithm protocol, system requirements for message acknowledgement, transponder delay time, and relay node processing and queueing times.

For dedicated channel algorithms, the transmission time delays are principally due to distance traveled and available transmission bandwidth. Circuit switched algorithms have the same limitations as dedicated channels in terms of transmission speed. The fundamental time delay is proportional to $\tau = d/c$, where c is the speed of light and d is the sum of the distances between the nodes connecting the terminals. For a single geosynchronous satellite connecting two terminals on the ground, the delay is 0.24 to 0.27 second, depending on the locations of the terminals relative to the satellite.

Certain network protocols lead to unduly long time delays among satellite nodes and should be avoided. These protocols are those which demand a message receipt acknowledgement (ACK) before sending each data block. A solution to minimizing time delay among satellite nodes is to:

- Use long data blocks, and
- Initiate transmission of a given data block without waiting for ACK to be received on the previous block.

Another contributing factor is the transponder delay time or the time required for the signals to propogate through the amplifiers and the frequency translation or demodulation and re-modulation processes

within the transponder. In general, it is on the order of m/B, where m = number of stages and B = circuit bandwidth. For a 2000 MHz bandwidth transponder of ten stages, the transponder delay time thus would be on the order of $10/2\times10^{9} = 5\times10^{-9}$ sec., which is negligible compared with the fundamental propagation time delay.

On board processing and queue times are highly variable and may well constitute the greatest time delays in many situations. Included are such functions as:

- Address recognition and message or packet switching time.
- Data queues, while data is awaiting complete processing.
- Actual processing time to achieve data compression, culling of most significant values, special computations, motion detection, or some other processing function.

Message switched algorithm time delays generally are a function of both distance and channel band width. Since each message must be received in total before it can be relayed to another node in the network, delays are proportional to the size of the message and the number of nodes traversed. In addition, a message can be forced to wait in a queue at each node between the source and user. Queueing delays are proportional to the total traffic in the communication system. Thus the larger the number of network users and the larger the message transmission sizes, the larger the delays for any given message of any size.

Packet switched algorithm time delays are also a function of transmission distance and channel bandwidth. At each node along the way, independent decisions must be made to determine the next node to send each packet. Each individual computation can be designed to be minimal, but their total time accumulation may be significant if a packet must travel through many nodes. Queueing delays for packets are generally less than those for message switched algorithms since the packets can be handled uniformly. Another advantage of packet switching over message switching is that portions of a message can be retransmitted before the entire message is sent. Of course, the potential bandwidth of a communication path can be increased when the satellite communication system architecture supports parallel interlinks between nodes.

In summary, dedicated and circuit switched algorithm transmission time delays are proportional to distance traveled and interlink bandwidth. The effective bandwidth can be increased by creating independent parallel interlinks and selecting data management algorithms to coordinate exploitation of this resource. Message switched algorithm time delays are particularly sensitive to the number of nodes traversed, size of messages, and total traffic within the communications network. Packet switched algorithm time delays are less sensitive to these factors. In particular, packet switched based transmissions are relatively independent of the size of transmissions of other network users. Depending on the system architecture, packet switched data management algorithms offer the opportunity for effective exploitation of parallel paths through the network to increase the relative transmission bandwidth between any given source and user nodes.[4,6,11,40*]

4. Connect Delay Time

The time required to set up a communication between an information user and information source is the connect delay time. This time is highly dependent on the particular data management algorithm used. The dedicated channel approach is a trivial case, since this time is negligible by design, i.e., there should always be an open line between each pair of communicators.

Circuit switched algorithms can have large connect delay times. Each time that communications are required a route must be determined and all required resources must be allocated to the communication circuit. Since individual interlinks may not be shared, it is possible for all circuit resources to be allocated, forcing the new communication request to receive a busy signal. In a priority-based system, a higher priority transmission may "bump" a lower priority transmission. The actual implementation for this "bumping" may be quite complex in order to prevent the loss of lower priority information. Depending on the network architecture, considerable processing may be required for the actual circuit set-up. Furthermore, if central controls are used, then additional time will be spent communicating with the controller to set up the new circuit. It

* References are given in Appendix C, Project Bibliography

has been estimated that this circuit set-up time may range from 30 seconds for a simple satellite architecture with no interlink contention to several minutes for more complex and highly used circuit systems. If the system is operating at saturation and/or poorly tuned, circuit set-up delays of hours may occur. For example, this already occurs on some computer networks where it is necessary to request a communication circuit hours in advance of the expected time of computer use.

Message switched algorithms generally do not have an appreciable connect delay time problem. One reason is that message switch systems typically are not used for interactive (two-way) communications and consequently, the significant time delay is that needed to transmit a message. However, there may be delays in entering a message into the network. This delay is usually due to the queueing capacity and flow capacity of the node receiving the message. These delays are highly dependent on the physical characteristics of the node processing and storage resources.

Packet switched algorithms may have a small connect delay in addition to that of message switched algorithms. This delay is due to the time required for a packet to traverse the network to its destination, establish the communication, and then acknowledge that the communication path has been established. The time required would be at least twice the minimum transmission time, estimated to be between 5 and 30 seconds.

In summary, dedicated channels do not have any connect delay, while circuit switched algorithms have connect delays which can be very large and require much computational processing. Message switched algorithms are not generally measured by connect delay times. Packet switched algorithms have connect delay times that are at least twice the minimum transmission time plus, possibly, processing at one end of the communication path.[6,11]

C. Communications-Related Considerations

A number of algorithm design factors must be considered which relate to the communications functional level of Figure II-1. These include

communications system

- Reliability
- Vulnerability
- Service Security
- Service Flexibility
- Efficiency

A discussion of each of these factors follows.

1. Reliability

High reliability is essential for any military communications system. For any communications network, data management reliability is the performance factor describing the ability of the communications system to perform its functions. Reliability is a component of system failure and includes:

- Mean time between failures
- Percent resends of data transmissions
- Mean time to repair

In a dedicated communications system, reliability is the overall product of individual component reliability since the system is designed to support only one application. Moreover, single application support sometimes produces simpler systems and, thus, more reliable ones. In the case of a dedicated satellite communication system, the addition of other features to optimize other performance factors could cause the system to be more complex than similar ground-based systems. In this case, the dedicated satellite data management may be less reliable than alternative approaches.

For circuit switched data management algorithms, the reliability is proportional to the average number of nodes in a circuit in addition to a factor proportional for the complexity of circuit switch technology. In addition, the greater the number of alternate circuits, the greater the reliability for the complete circuit switched algorithm-based communication system.

For a message switched data management algorithm, the number of alternative paths available for a message transmission contributes to the system reliability. However, due to the nature of the system (i.e., entire messages transferred between nodes), single node reliability greatly affects the system reliability. This is an inherent weakness of this approach.

For a packet switched data management algorithm, reliability is also proportional to the average number of nodes traversed by a packet. However, reliability is enhanced over that of message switching due to the inherent nature of packet switched algorithms which optimize the transmission of small information units. For example, a packet switched algorithm may take advantage of the ALOHA positive acknowledgement technique which has been found to have minimal effect on total transmission time.

In summary, dedicated channel and message switched based approaches may be less reliable than the alternative algorithms due to features that must be added to ensure total system usefulness. Circuit switched and packet switched based approaches have built-in features that add to their reliability. It seems evident, however, that packet switched data management algorithms can be the most reliable general purpose approach due to the opportunity provided by a variety of parallel interlinks available for transmission of each packet of a total information unit.[31]

2. Vulnerability

Vulnerability describes how a communication system withstands unauthorized access, jamming, spoofing, and destruction. For each space communication system, the critical components are the satellites themselves, the interlinks between satellites and to the earth, and the ground nodes. The satellites are vulnerable to destruction, but can be somewhat protected by having sufficient redundancy in their various components. For dedicated channel system, redundancy may require additional satellite nodes. This can be very expensive since these extra satellites

may not be used unless needed (of course, if they were used then the system is no longer dedicated). For the other data management algorithms, redundancy can be built-in since each is based on the sharing of resources. The loss of individual interlinks between satellites or between the satellites and ground is equivalent to jamming. This problem can be tolerated with sufficiently redundant interlinks between information source and user.

Protection against unauthorized access and spoofing of a satellite communication system requires that the system contain access controls. These controls should be dynamic to assure more complete protection than solely using static access controls. This means that processing is required both to allow access to the system and to determine whether spoofing or unauthorized access occurs during system operation. In a dedicated system, this processing would have to be accomodated with the basic communication resources. It adds to system complexity and overall expense. For circuit switched based approaches, the static processing could be incorporated into the original circuit set-up processing. However, any dynamic protection processing would also require a specially designed processing capability to be added to the system. For message switched and packet switched based approaches, the processing could be incorporated into the required switch processing onboard the satellite nodes. Since packet switching readily supports bidirectional interactive communication (in contrast to message switching), necessary packet switched algorithms can incorporate protection techniques into the network bidirectional protocols. Both the bidirectional nature of packet switching and the fact that messages are divided into small data packets which can be routed independently (a built-in protection) lower the vulnerability of this algorithm. It also appears that the amount of extra vulnerability processing required for packet switched algorithms may be smaller than with other approaches.

3. Service Security

Service security refers to the method required to protect information transmitted between the information source and the information

user. Encryption is the basic technique used for information service security and would be required for each of the alternative data management algorithms. Packet switched algorithms offer a potential additional means for security since each packet contains a small amount of a total transmission and most packets must be intercepted to intercept a complete message. In addition, if parallel interlink transmissions are possible, then the interception of the packets may be difficult. Parallel transmission is easy for packet switched algorithms, but can be difficult for the other data management algorithm approaches.[25]

4. Service Flexibility

Flexibility describes how well the communication system can handle a variety of information flow demands. This factor covers the variety of information unit sizes, rates and communication priorities. By definition, dedicated channel systems have no built-in flexibility. Instead, the users must decide for themselves on types of information units transmitted and how to interrupt transmission if necessary. Circuit switched algorithms are similar to dedicated systems in their flexibility except that it is possible to restructure the communication circuit network under priority demands.

Message switched algorithms are relatively flexible. It is possible to assign a priority to each message and use it to help determine how messages flow through the network. As has been previously noted, under a message switched approach, the existence of large messages in the system can significantly slow the transmission of short messages. Similarly, packet switched algorithms can handle communication priorities like message switched algorithms. The size of individual information units mostly affects the transmission of that information and no others. In this respect, packet switched algorithms seem the most flexible among the various data management alternatives.[22]

5. Efficiency

Communications system efficiency may be measured in two ways: one from a systems view and the other from a unit transmission view.

From the systems view, efficiency reflects how well the system processing and transmission resources are utilized. This efficiency measure is directly related to the actual sharing of these resources.

A principal reason for considering the use of multi-mission space communications networks is to take advantage of sharing expensive and possibly scarce resources among several system users. Dedicated systems by definition have no resource sharing. Thus in a truly dedicated satellite communication system, each user or generic application, such as surveillance, meteorology, RPV control, or others, will require a completely separate satellite sy em. Circuit switched systems share resources among users, but are highly inefficient when circuits are assigned and not being used. Message switched and packet switched data management algorithms permit the sharing of communication network resources very well among the system users.

From a unit transmission view, the concern is with the efficiency of transmitting an information unit measured as a function of required overhead for that transmission. Since both dedicated systems and circuit switched approaches do not require destination addressing or routing information, the only overhead involved would be due to satisfy reliability requirements.

In store-and-forward routing approaches, some form of information unit reliability overhead is required of each alternative data management algorithm. For message switched algorithms, the overhead is proportional to the extra data that must be transmitted to identify the message, its destination, and sometimes its routing. For small messages this can be significant, but for large messages the overhead will most likely be small. For packet switched algorithms, the overhead for an entire message is the sum of individual packet overhead values. The larger the number of packets per message, the greater the information unit overhead.

In summary, dedicated and circuit switched systems are inefficient with respect to resource sharing but have relatively low information overhead. Message switched algorithms efficiently share reso rces

and have overhead that decreases with information unit size. Packet switched algorithms have highest efficiency resource sharing but are the least efficient in terms of overhead required per information unit size.

D. Performance Measures

Of the several basic considerations essential to selection of a satellite data management algorithm, much importance must be placed on those functional operations used to transmit information from its source to its users. In order to judge the success of the operation of specific algorithms employed, performance measures of data management algorithms are used as a means to quantify the performance of the data management functional operations.[31]

There are two points of view concerning the performance of a data management system. These viewpoints concern (1) the operations of the system and (2) the use of the system. For some criteria, these viewpoints agree on levels of importance and optimization, but there are many performance criteria on which the viewpoints will diverge concerning relative importance across representative military missions to be supported. In the worst case, each individual mission will require the optimizing of different performance criteria indicated by these measures.

Several performance criteria are of importance. These include:

- Efficiency of Data Compression
- System Capacity
- System Availability
- System Use
- Distortion and Noise

A discussion of each of these factors follows.

1. Efficiency of Data Compression

Data management algorithms encompass the compression of data for transmission and its subsequent reconstruction. There are two distinct

classes of data compression algorithms: one-dimensional, as applicable to text, data and voice encoding, and multi-dimensional, such as the two-dimensional algorithms applicable to image encoding.[35]

Much of the work on algorithms for one-dimensional source data compression is based upon the Huffman codes, which are variable-length codes for characters and chatacter strings. Other techniques include fixed length coding for character strings, binary data compression, such as run length encoding, and irreversible compression codes, such as transition distance coding, the soundex code, and others.[26,39]

The Karhunen-Loéve Transform (KLT) is optimal with respect to variance distribution, mean square error mimimization, and rate distortion, but lacks an algorithm enabling its fast computation.[35]

The Discrete Cosine Transform (DCT), on the other hand, results in a very small increase in mean square error over the KLT, but can be computed with an algorithm using the Fast Fourier Transform (FFT). The M DCT coefficients can be computed using a 2M point FFT.[35]

A low complexity data compression technique developed in connection with the Earth Resources Technology Satellite (ERTS) Program is tailored to the characteristics of multi-spectral data. It can be implemented to provide compression ratios in excess of 2:1 at over 100 M bps with zero distortion. It is known as the Spectral-Spatial-Delta-Interleave (SSDI) algorithm. The SSDI operates on the spatial redundancy in each spectral band, and then uses the result to reduce spectral redundancies between adjacent bands.[35]

Differential pulse code modulation (DPCM) is used to form pixel differences along each scan line. Then second differences (Δ's of the Δ's) are formed. On the average, the second differences are less than the first differences because of spectral correlation. A triple of the interleaved first and second differences then allows reconstruction of the pixel. For each pixel, one spatial difference and three spectral differences are sent.

The compressed bit stream consists of source encoding of the differences symbols and this encoding is based on the statistical occurrence of the diffenences symbols. The techniques used include the Global Huffman, Adaptive Huffman, and the Universal Rice.

An SSDI improvement, known as SSDIA, uses a block of contiguous pixels to generate first difference symbols. It obtains a higher average compression than SSDI by exploiting the two-dimensional correlation. In addition, it smooths sensor and sampling noises through averaging.

A further improvement, SSDIAM, allows the mapping of original pixel intensities before the first differences are formed. (The "mapping" restricts the intensity levels.) A small amount of distortion is then allowed in the reconstructed data, in return for which a higher compression ratio is achieved.[35]

2. System Capacity

The capacity of a data management network is defined to be the amount of information that can be delivered to the end user node. There are various components to the measure of system capacity. The usual units for measuring capacity include the number of available channels, channel band-width, and computed baud rate.

From the operational viewpoint, transmission capacity in terms of bit rates and numbers of channels is an important basis for capacity. For the user, applications oriented information is more important. Thus, if processing is performed in the satellite communications system to send only pertinent information to the ground, the capacity is based on that quantity of information.

For example, if a user is interested in counting the numbers of buildings in a certain sector, the picture processing could be performed on either the ground or at the sensor. When a ground-based node is the processing unit, the entire picture description must be transmitted. However, if the processing is performed in a satellite-based source or relay node, only final figures need to be transmitted to the ground. The end user observes the same system capacity (assuming devices with

the same resolution), but the satellite network need support a much smaller amount of data transmission capacity when processing is performed in orbit. Naturally a drawback with orbit processing is that raw data is lost and thus can not be processed for other concurrent or future applications.

3. System Availability

An information network such as the envisioned multi-mission space communications system is only useful when it is operational. Thus the very simple criteria of system availability is useful to both these responsible for operating the system and especially for those using the system. The methods used for measuring availability are fairly simple and are usually stated as the percentage of up (or down) time.

System availability is an extremely relative term. For example, the space communications network may be excellent for all of its functions but it may lose its usefulness if it is only operational 1 hour per day when the need is for 15 hours per day. The reasons for the lack of availability do not matter to the user and as such he does not care whether the service is down due to failure, politics, maintenance, or other reasons. Of course, the operations personnel are likely to be more concerned with the reasons for lack of availability, but the users' availability demands must be paramount.

4. System Use

Closely allied with the performance measures of system capacity and availability is the relative measure of system use. As used herein, system use is a measure of the use of the processing and transmission resources of the satellite communications system. The data sources on which use measures are based include (1) counting actual data transmission traffic in terms of message bits, characters or other appropriate units, (2) measuring message sizes, and (3) message frequency and other traffic measures. It is, however, more a measure of how much of the potential system capacity is being used.

From the operations viewpoint, system resources should probably be highly employed so that little of their potential goes to waste. However, high usage often provides lower service based on such user criteria as error rate, response time (transmission time), and possibly even security. Thus the user's interest is often for somewhat less than maximum potential when there may be an associated degradation of service.

As a performance measure, an optimum percentage of resource use consistent with transmission priorities is difficult to determine. A 100% utilization, or close to it, means a system that is on the verge of overload and which may quickly develop long queues if all possible input data requires eventual transmission. A relatively poor usage may mean the system has the capacity to tolerate surge overloads, but may be difficult to economically justify.

5. Distortion and Noise

The actual information content that is transmitted may be altered due to the transmission process. This is known as distortion. For example, contributing factors to the transmission error rate or distortion:

- Image Element Size (inverse to bit rate)
- Quantization of Image Element (inverse to bit rate)
- Random Noise in Channel (of concern in marginal channels)
- Data Compression Effects

The typical performance measures that are used for data management algorithm purposes include (1) errors/message/time, (2) number of resends.

Depending on the applications, a certain amount of distortion may be acceptable. For example, the transmission of voice or other relatively low information content data may be understandable with a high degree of modification of the input data. Unless high resolution is required, pictures may also be acceptable with noise and distortion. However, as the data is processed at its source, it becomes less redundant

and more compact, and thus distortion and noise can become a problem. As with other criteria, the particular application probably will provide the basis for the acceptability of distortion and noise.

E. A Comparative Evaluation of Data Management Algorithms

Tables V and VI present a summary of satellite data management algorithm alternatives, with regard to mission considerations and with regard to communication systems considerations, respectively. Of course, a mission-related comparative evaluation cannot be made until specific mission information exchange requirements for each specific mission to be supported are identified. As a first comparison, however, the generic mission requirements discussed in the previous chapter may be used for this purpose.

It may be seen in Tables V and VI that dedicated channel systems handle all information unit sizes and information rates. In addition, dedicated channel systems have no connect time and minimum transmission time. They are ideal in support of a single purpose mission. Without other considerations (such as cost and resource sharing), dedicated lines appear to be a better choice. For multi-mission support, however, as well as effective resource sharing, packet switched data management algorithms appear to be the preferable choice in the implementation of a multipurpose communication system. Packet switched data management algorithms will handle mixed information unit sizes, medium and large times between transmissions, short system connect times, and a wide range of transmission times.[4,6,11,13,22]

TABLE V

MISSION COMPARISON OF DATA MANAGEMENT ALGORITHM ALTERNATIVES

Information Unit Size

Mixed:	DC,CS,PS
Small:	DC,CS
Medium:	DC,CS,MS
Large:	DC,CS,PS

Information Rate of Occurrence

Continuous:	DC,CS
Small:	DC,CS
Medium:	DC,CS,PS
Large:	DC,CS,MS,PS

Time to Connect

None:	DC
Short:	PS
Longer:	CS

Transmission Time

Minimum:	DC,CS	
Moderate:	MS,PS	Note: PS significantly lower than equivalent MS operation
Large:	MS,PS	

Key: DC - Dedicated Channel
CS - Circuit Switched Algorithm
MS - Message Switched Algorithm
PS - Packet Switched Algorithm

TABLE VI

SYSTEM COMPARISON OF DATA MANAGEMENT ALGORITHM ALTERNATIVES

Resource Sharing

Low:	DC
Some:	CS
Much:	PS,MS

Vulnerability (Required Additional Processing Power)

Little:	PS,MS
Some:	CS
Much:	DC

Reliability (Inherent)

Low:	DC,MS
Moderate:	CS
High:	PS

Service Security

Same for all; inherently PS can be most secure.

Service Flexibility

Low:	DC
Medium:	CS,MS
High:	PS

Efficiency

Low:	DC,CS
Moderate:	MS
High:	PS

Key: DC - Dedicated Channels
CS - Circuit Switched Algorithm
MS - Message Switched Algorithm
PS - Packet Switched Algorithm

CHAPTER V

SATELLITE NETWORK DATA MANAGEMENT OPPORTUNITIES

A. Introduction

The previous chapters have developed the foundation for an evolutionary satellite communications network and the fundamental considerations for data management algorithms for such a network. From this basis, it is possible to establish an evolutionary set of critical issues relative to satellite network data management opportunities. Four critical issues are identified:

- Development of Desired Mission Requirements
- Availability of Necessary Technology
- Practicality of a Multi-Mission Network
- Potential to Improve Information Use and Presentation

Each is a necessary consideration in order to bound data flow algorithms and assess the impact of such rules on network capability.

These issues represent both opportunities and limitations relative to the ultimate success and utility of a multi-mission space communications network. A discussion of each of these four satellite network data management issues is presented in the following sections of this chapter.

B. Development of Desired Mission Requirements

It is obvious that specific mission communication requirements must be established before data management algorithms for that mission can be further developed. In particular, it is necessary to develop actual information exchange requirements for all missions to be supported. These

include:

- Information-Flow-Related Factors, such as:
  - Timeliness
  - Priority
  - Access Control
- Information-Use-Related Factors, such as:
  - Availability
  - Application
  - Routing/Distribution
- Technical Parametric Factors, at a minimum:
  - Information Rate
  - Duty Cycle
  - Data Redundancy
  - Number and Geographic Distribution of Sources and Users
- Node-Related Factors, such as:
  - Function and Location
  - Threat Environment

The utility of these factors has been considered in Chapters II through IV and will not be repeated here.

Clearly, as was shown in the comparative generic requirements of representative missions in Chapter III, there is often an inherent disparateness in the simultaneous support of more than one mission. Nevertheless, mission requirement support tradeoffs can be found through creative compromise and the application of sophisticated data management algorithms, such as packet switched approaches.

It is strongly felt that this issue represents the most important opportunity to be developed in future satellite data management efforts.

C. Availability of Necessary Technology

In the detailed consideration of satellite data network opportunities, it is necessary to postulate the availability of necessary network technology as well as to identify inherent technological limitations. As

used herein, "technology" considers the physical realization of the envisioned network using existing computer, communications, and satellite components or reasonable extrapolations thereof. Although a thorough technological assessment was beyond the scope of this study, many sources of technology projections through through the year 2000 and beyond were found readily available.

Critical technology areas which affect the implementation of algorithms are:

- Logic Circuit Components
- Processor Architecture
- Computational Performance
- Memory Systems (operational control and data base)
- Spacecraft Power Sources
- Spacecraft Transmitter Limits (power and bandwidth)
- Antenna Performance Limits
- Satellite Lifetime

In general, these critical technology areas are each well established disciplines, with many simultaneous research and development programs now underway. For each area it was found that, although requiring state-of-the-art technology (and in some cases, "blue sky" extrapolations) for realization in the next two decades, the technology necessary to support required data management algorithms seemed feasible with a reasonable probability of attainment.

For example, it is necessary to estimate on-board satellite node processing requirements for specific data management algorithms in support of specific missions. This estimation must consider basic computation sizing parameters such as:

- Processing Bandwidth
- Memory Capacity
- Distributed System Architecture

Additional considerations in development of these requirements include:

- Physical Size and Weight
- Power Requirements
- Reliability

Specifically, these computation requirement estimates must consider:

- Data Compression Algorithms
- Network Resource Utilization Algorithms
- Alternative Processor/Network Architecture

It may be postulated that in support of these requirements, each node of a satellite-based data network may employ one or more:

- General-Purpose Processors
- Special Purpose Processors, such as:
  - Pipelined Architecture
  - Parallel Architecture
    - Array Processors
    - Multiprocessor Configurations
  - Associative Processor (logic-in-memory architecture)

to implement each distinct data management algorithm. Of course, the applicability of these potential processor/network architectures to specific data management algorithms is dependent upon:

- Inherent Parallelism in the Algorithm
- Algorithm/Data Dependencies (computational independence)
- Data Base Organziation Considerations

Three especially critical technology areas were identified. These were:

- Interlink Data Rate
- Frequency Selection
- Link Privacy

1. Interlink Data Rate

It is found that the high data rates (say 10^{12} - 10^{15} bps) required in interlink transmissions may not be supported by postulated

technology. In particular, interlink data rates to support a general multi-mission packet switched network may not be adequate.

For example, consider Air Force/NASA forecasts for A. D. 2000 possibilities[37]:

- Satellite Interlink (CO_2 Laser): 10^{10} bps
- Low Altitude to Synchronous Satellite (CO_2 Laser): 4×10^9 bps
- Deep-Space to Near-Earth (Laser): 10^8 to 10^{10} bps
- Earth to Synchronous Satellite (Microwave): 10^{14} bps
  - Multi-Beam Antenna (50 - 20 G bps Channels at 40 GHZ)
  - Data Compression of 100:1
- Portable Terminal Earth to Synchronous Satellite: 4×10^8 bps

2. Frequency Selection

An intrinsically related issue to interlink data rate is frequency selection. The space-earth link may be a critical bottleneck. The following summarizes frequency-related limitations:

Space to Space: Few Propagation Limitations above ionosphere identified to date

Space to Earth:
- Below 2 GHz not generally suitable
- 2 to 10 GHz Range is optimum for propagation, but heavily used
- 10 to 300,000 GHz range contains numerous propagation "windows": space diversity on ground aids in overcoming precipitation attenuation
- Higher frequencies subject to atmospheric scintillation effects

3. Link Privacy

The link privacy factor seems an area with low technological potential without the use of highly directive laser interlinks. Yet link privacy is an especially important implementation consideration, in that link privacy is critical to network penetration/jamming/spoofing vulnerability issues.

Link privacy may be achieved by:

- Use of extremely narrow beam widths
- Transmission behind propagation barrier
- Use of special coding techniques

It is noted that the first two requirements may be met with laser inter-satellite links, although laser interlinks are not as effective on the space-earth link due to propagation considerations. In this case, special coding techniques appear most promising.

D. Practicality of Multi-Mission Networks

As a philosophic issue, it is necessary to assess the ultimate practicality of a multi-mission network. This assessment must be done with respect to both the multi-mission network users and the implementation feasibility tradeoffs (e.g., mechanical/systems detail constraints and potential). At a minimum, this assessment must consider issues of:

- Time sensitivity of information transmission vs. time delay inherent in
  - Switched network queueing delay
  - Multi-satellite link overhead
  - Geostationary orbit link delay
- Resource contention among missions
- Extent of permissible resource reduncancy
- Desirable percentage of resource utilization
- Network operation at saturation loads

Again, specific considerations for each of these factors have been considered in previous chapters of this report.

On both a conceptual and a practical plane, it is possible to identify various inconsistencies and mutual exclusions relative to support of various military missions. The most critical issue clearly seems to be the inherent time delay of a satellite relay, especially a multi-hop satellite relay, in support of certain time-sensitive missions.

It is necessary to consider the entire set of potential missions to be supported to determine which ones are sensitive to time delay, and thus

unable to tolerate the delay of a multi-hop satellite system. A review of representative military missions has indicated that there are no missions in which it can be categorically stated that a double-/or triple-hop delay is intolerable. However, those missions that are delay sensitive are those involving:

- Attack warning, where timely target point prediction and trajectory estimation are are of primary importance
- Control loop response speed and stability

For example, representative attack warning missions include:

- Ballistic and FOBS Detection
- Advanced Aerospace Defense
- Missile Launch Indications

Similarily, examples of representative control loop response situations are:

- RPV Control
- Missile Tracking

The time required for the data processing needed to perform targeting and trajectory prediction is a complicated function of the number and quality (or noisiness) of the available data points, the processing algorithms and circuit speeds available, and the a priori knowledge available about the object launched, as well as its firm identification. Values range all the way from under a second to four to six minutes or more.

The ultimate practicality of a multi-mission network is most probably a function of the compromise attained in the support provided to various time-sensitive missions. Other aspects, including issues of resource redundancy, resource utilization, and levels of network saturation, are important but secondary considerations in the realization of a truly multi-mission space communications system.

E. Potential to Improve Information Use and Presentation

The final critical issue relating to satellite network data management opportunities are considerations of the ultimate overall (information source to information user) system information use and presentation to the end user. This issue involves the potential for the data management algorithms of the envisioned space communications network to provide

as well as support:

- Distributed Data Processing
- Distributed Information Storage
- Dynamic/Adaptive User Interfaces (Reprogramming Capability)
- Information Fusion

Effective data management algorithms can be developed to supply total information transmission and processing from source to user. This requires the communications system be considered on information network that can provide the ultimate information user with a formatted display of all desired processed information with optional information transformation characteristics. Consistent with the information network model developed in Chapter II, the information source and user must be capable of maintaining an interactive dialog in a dynamic/adaptive information exchange.

Although a significant extension of current command communications systems capability, this idealized information network must additionally provide multi-source information processing and fusion in support of the total decision requirements of the end user. It is potentially feasible to consider such a multi-mission communications system to provide fully integrated and fused data from strategic, tactical, operational and intelligence sensors necessary to the decision process, as well as to provide fusion of real-time sensor data with remote data base retrieval to support the human intellectual/analytic process. These latter issues relative to <u>total</u> information processing and presentation to best meet the overall information requirements of the end user seem the most compelling of satellite data management opportunities.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

A. Introduction

This concluding chapter presents a brief summary of the results of the SAMSO-sponsored Satellite Data Management Algorithms Study. Several key required technological developments identified in the course of this effort are also discussed. The final section of this chapter additionally includes recommendations of satellite data management algorithm areas requiring continued investigation in subsequent advanced space communications research and development programs.

B. Summary and Conclusions

Satellite data management algorithms consist of all the rules which govern information flow in a multi-satellite space communications network. As such, satellite data management algorithms must encompass basic data communications functions and processes, including:

- Network Control
- Network Routing
- Data Compression
- Channel Assignment
- Adaptive User Feedback
- Error Detection and Correction
- Security/Priority Considerations
- Distributed Data Management
- Performance/Resource Optimization

This study has necessarily concentrated on issues of network control and routing, although considerable emphasis was given to peripheral issues of network architecture options and user requirements. There is a substantial interrelation between information exchange functions, connection-oriented functions and communications-oriented functions, all of which are the domain of network data management algorithms (see Figure II-1). Specific mission-related algorithms studies were hindered by a substantive lack of quantitative mission information requirements, such as actual information quantities, necessary transmission rates and the geographical distribution of sources and users.

Representative military space activities used in this effort were the surveillance, meteorological and RPV missions. Such diverse missions were selected to provide a disparate variety of information-exchange-related attributes to best test the potential of a multi-mission space communications system.

Several conclusions are relatively straightforward. The multi-mission communications objective appears best supported by use of distributive supervisory control algorithms and a priority scheme that allows urgent messages to pass unhindered by network blockage from low-priority messages. Network routing algorithm selection is not as clear and requires considerations of various operational tradeoffs relating to actual mission characteristics. In the whole, some form of variable routing algorithms, such as distributed packet switched routing algorithms, seem the most reasonable compromise to accomplish effective sharing of transmission and processing resources among the various missions. System extendability is significantly facilitated by packet switched routing algorithms.

Specific packet switched routing issues which must be further evaluated with respect to actual mission requirements are:

- Network Routing Overhead
  - Adaptive control is best
  - Distributed decisions across network are best
- Packet Sizing Overhead
  - Large packets are more efficient
  - Small packets are more reliable

- Error Correction Overhead
  - Moderate overhead per packet requires few retransmissions
  - Small overhead per packet implies expected retransmissions
- Security Control Overhead for
  - Penetration suppression
  - Anti-jamming/spoofing measures
  - Resource diversion safeguarding

In general, packet switched based network data management algorithms tend to best support multi-mission applications where transmissions are intermittent, delay must be minimized, messages are of various lengths (mixed long and short) and simultaneous transmission of packets can be accomplished over parallel interlinks. This latter feature is a principal advantage of packet switched algorithms over comparable message switched algorithms. It was also determined that overall time delay is the most critical consideration for certain missions, such as RPV control. In this case, the larger time delay inherent in packet switched algorithms over circuit switched algorithm alternatives may heavily weigh against their use.

C. Identification of Areas Requiring Further Technological Development

Ten key issues have been identified during the course of this study in the area of required technological developments. Each is discussed in the following section.

1. Man-Machine Interface

What data does the user need in order to perform his mission most effectively? Does he know what he needs, how to request it, and how to interpret it?

The problem facing the user is typified by his having to perform the following functions:

- Sifting through very large quantities of data to reduce their volume and extract information relevant ot some purpose.

- Applying heuristic procedures to limit or accelerate search in the exploration of decision trees too large to be followed to conclusion.
- Building, maintaining and accessing large information bases whose application and content may change.
- Controlling many concurrent procedures with competing requirements and changing priorities.

The man-machine interface is characterized by both displays and software. The ease with which the user can access data sources via the network is directly related to the expertise needed to develop and use the required software. Simplified or higher order machine languages may help to solve this man-machine interface problem.

Correspondingly, the need exists for computer systems that can understand human language. The computer must match man's intellectual and sensory abilities to acquire and assimilate knowledge. This calls for the refinement of systems that provide large vocabularies and sophisticated language capabilities so that they are convenient to use and compatible with human capabilities.

2. Data Interpretation and Information Fusion

Closely related to the issue of the man-machine interface is that of data interpretation and the merging of disparate information elements. The cost of timely data interpretation and subsequent multi-source information fusion is a key factor limiting the amount of valuable source information which can be obtained from future space missions. The need thus exists to automate much of the data acquisition and data interpretation process. Much of this implementation should be possible by developing programs for use within intelligent spaceborne nodes (satellites with on-board processors).

3. Data Compression

The steady increase in the amount of information to be collected, processed and disseminated by space missions forces the development of advanced data compression techniques. These techniques include the automatic recognition of redundancy in images and the application of data compression without loss of content. Four classes of applications which

have been identified are those requiring:

- Exact or nearly exact reconstruction of the original source data.
- Approximate reconstruction of the source data, with very little perceptible difference between images produced from the compressed data and from the original.
- Production of high-resolution thematic maps which describe the spatial distribution of a small number of source "classes" that are recognizable from the spectral properties of original data samples.
- Determination of the location and the key parameters of prescribed features that occur infrequently within a survey area.

On-board processing must be developed to allow a high degree of data compression to be accomplished, and to facilitate quick reaction to discovered targets of opportunity.

4. Distributed Computation

The development of distributed computation, of intelligent terminals, and of networks that tie them together provide users access to a wide variety of different computational facilities whose languages and conventions may be unknown to these users. The use of distributed computations has been a basic assumption underlying much planning of future space missions. However, the computational capabilities residing within the Army, the Navy, and the Air Force cannot all be linked together readily. One way of making distributed computation a reality is by adapting machines to the conventions of natural human languages.

5. Network Security Measures

Technological development is needed to prevent interlopers from ascertaining what is being transmitted on communication links. Although the use of encryption goes a long way toward this objective, increased security is needed at the terminals themselves, where decryption has taken place, or before encryption has occurred.

The key issues with respect to the links themselves are the problems of jamming and physical threats to the satellite nodes.

6. Data Rate Limits

The factors limiting channel data rates have been identified in this study as the circuit speeds with which modulators and demodulators can operate, rather than inherent bandwidth factors of tubes, solid state devices, or lasers themselves. Moreover, data stream serializers and synchronizers (for combining and partitioning data streams) present comparable limits (on the order of 1 to 2 Gbps) at the present time. This area warrants substantial development, especially in view of the fact that many satellite links can provide excellent received signal-to-noise-power-density ratio values (e.g., 30 dB), with consequent high ratios of bits/second per Hertz bandwidth (e.g., 10), through the use of high order digital modulation techniques.

7. Power in Space

The future use of space shuttle technology allows spacecraft with the ability to carry volumes and weights of solid state components that cannot possibly be powered because of the relatively low levels of solar power available. This fact calls for an accelerated development program in the area of radio-isotope thermoelectric generators in order to maximize the amount of on-board processing capability possible on a satellite of given size.

8. Links Between Maneuverable Platforms and Satellites

Maneuverable platforms (aircraft, helicopters, jeeps, etc.) often must have small antennas that are either low in gain or, if of high gain, require careful pointing toward a satellite in order to maintain their links. Furthermore, maneuverable platforms are characterized by limited primary power capability, plus widespread demands for the power that is available. The development of improved tracking systems, highly accurate ($<0.1^{o}$), small (<0.1 kg) and very agile, thus becomes important. The use of electronic (as distinguished from mechanical) beam pointing them is indicated.

This requirement is important not only for maneuverable platforms, but also for fixed platforms operating at frequencies above 15 GHz, at

which the problem of atmosphere-induced beam wander becomes significant, and requires a tracking capability also.

9. Frequency Re-Use Techniques

Present military satellites have an inadequate number of channels because of limited spectrum availability. Although the future multi-mission satellite system probably will operate at frequencies that are not presently crowded, steady increases in data rate demands call for the most efficient possible use of the spectrum. This demands the extensive application of frequency re-use techniques. Such techniques need further technological development above 15 GHz. They include:

- Polarization diversity
- The use of multiple beam antennas, with numerous crossing beams between synchronous orbit and users on earth
- Space diversity

Although not a frequency-re-use technique, good spectrum usage above 15 GHz will call for the use of fast data dumps between satellite and earth during good weather conditions.

10. Development of Multiple Spot Beam Antennas

Spot beam antennas for use both on land and on board satellites for the 10 to 300 GHz frequency range, and having as many as 50 spot beams, are called for, and warrant serious development effort in the preparation of a multi-mission satellite system. The rationale for such development lies both in the areas of data rate requirements and efficient spectrum utilization.

D. Areas Requiring Additional Investigation

A number of areas for additional investigation which should be performed in subsequent phases of the Satellite Network Data Management Program have been identified. These include continued investigation to further provide an:

- Improved understanding of mission-information characteristics interrelationships

- Establishment of minimum time delay requirements
- Measure the extent of information redundancy in mission data
- Establishment of vulnerability/survivability/reliability requirements
- Development of optimum number of satellites in the multi-mission space network, to include considerations of the:
  - Extent of useable interlinks per mission
  - Bounds on network control overhead
  - Exploitation of parallel interlinks
- Evaluation of computer/communications/satellite technology interrelationships

Many of these issues can only be resolved through computer simulation of network data management algorithms. Several of these issues are further discussed in this section.

1. Development of Total Mission Requirements

For each of the military missions to be supported, it is necessary to develop a definitive forecast of communications requirements through the year 2000. These involve both node-related requirements/opportunities and network information-related requirements/opportunities.

Important key issues are:

- Node location (i.e., satellite vs. terrestrial)
- Node threat environment (at sources, relays, users)
- Node survivability and reliability considerations
- Information-flow parameters
  - Transmission characteristics
  - Information data rate
  - Duty cycle
  - Geographic distribution of sources and users

More generally, this development requires the answers, in both qualitative and quantitative terms, to the following questions:

- What does the user need in terms of total data communication? (Consider the requirements of all services.)

- What will the user be likely to have by the year 2000?
- What, therefore, would a multi-mission satellite system do for him?
- What presently unfilled needs exist (considering the requirements of all services), for which no firm solution (implementation) is planned?

The above requirements must then be translated into total data volume from each source location to each destination, accounting for simplex, half duplex and full duplex requirements. In other words, the planning for a multi-mission military satellite system must visualize the total data flow that the system must be able to handle in the year 2000. Other requirements include those for data processing and storage within the system. All of this information must be established quantitatively before the system can be sized; i.e.:

- How many data channels are needed at what rates?
- How many voice channels?
- How many video channels?
- How many interactive computer channels?
- Where are the terminal locations, and what is the expected data flow to and from each?

2. <u>Establishment of Minimum Delay Requirements</u>

For each of the missions, it is also necessary to establish the minimum tolerable delay between source and user. This then may establish certain physical propagation-limited constraints on the network architecture.

Important key issues are:

- What is the effect of the general network inherent delay on the mission?
- Can a general network support all desired time-sensitive information exchange?
- Are mission information exchanges inherently limited to
  - One single hop to a near-earth orbit satellite?
  - One single hop to a synchronous satellite?
  - Small number of multi-satellite hops?

3. Information Presentation to User

The user node may represent the greatest challenge to network design for effective utilization of system resources. Important key issues are:

- Data processing/data presentation trade-offs
  - Human factors considerations (preferred displayed information)
  - Presentation levels (alarm, changes, real-time data, storage recall)
  - Limitations on presentation and classified data
- Information utilization
  - Post-processing vs. pre-processing
  - Data fusion requirements/capabilities/opportunities

4. Characterization of Data Management Opportunities

Fundamental to the justification and planning of any network is the characterization of the data to be transmitted on that network. Such a characterization includes statistical information on message lengths, on-times, data rates, as well as overall user requirements.

A wealth of key issues involve characterization of the ground-based (terminal) data management so as to effectively utilize a satellite-based communications network. These include:

- Requirements for space diversity (constraints upon space-earth bandwidth)
- Interfaces with ground-based user nodes and own-force units
  - Type and quantity of channels
  - Data rate per channel

Tradeoffs must be performed for a wide variety of data management scenarios (combinations of paths, terminal locations, data types, data rates, etc.) between processing at the sensors, at nodes, and at user terminals. How much processing should be done where, and under what conditions for each requirement? The answers to these questions will establish processor and memory requirements within the network.

5. Concept Simulation

It would be most useful to perform a full-scale simulation of the conceptual generalized information network. Due to the complexity of the task, such a simulation is not likely. However, several data management algorithm design issues do lend themselves to simulation techniques. Specifically, these are the simulation of alternative data management algorithms in support of various military space missions for determination of:

- Alternative candidate information flow techniques (e.g., message-switched vs. packet-switched)
- Exploitation of link parallelism in routing
- Bounds on support for various mission combinations
- Optimum allocation of network resources
- Optimum satellite numbers and orbits
- Ease of penetration/diversion/jamming/spoofing
- Quantitative network overhead and time delay estimates

Such simulation techniques may be the only reasonable approach for effective resolution of the several multi-mission satellite network data management design issues previously identified in this report.

APPENDIX A

BASIC COMMUNICATION NETWORK CONCEPTS

1. Introduction

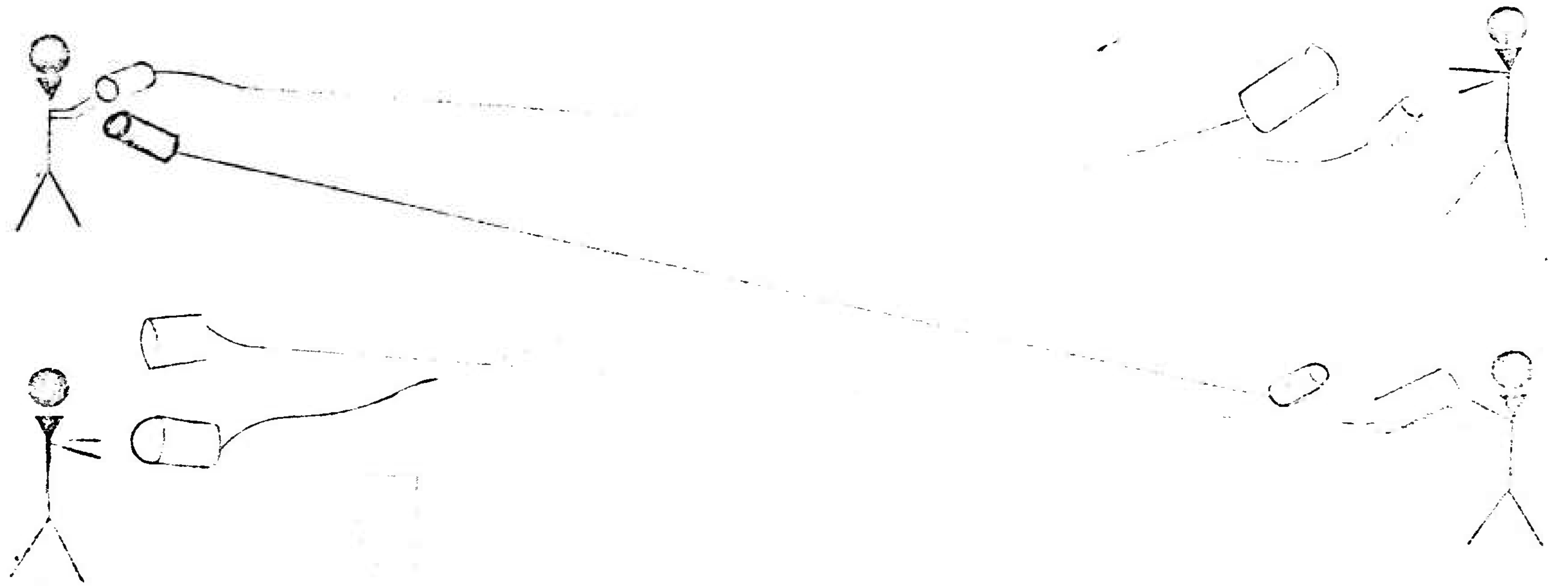
As currently practiced, there are four concepts describing the use of communications media for exchanging information between sources and users within a generalized information network.[6] These are:

- Dedicated channels, uniquely intertying one source with one user.
- Circuit (line) switching, as is done by the public telephone network.
- Message switching, as is common in the transmission of telegrams.
- Packet switching, as is becoming significant in computer communications.

The differences between the concepts relate to factors for resource sharing, transmission speed, system reliability, and others, as are described in the following paragraphs.

2. Dedicated Channels

The most basic approach to interconnecting one information source and one information user is to provide a permanent dedicated line for this purpose. Figure A-1 shows how several information users would use dedicated lines for communications. Each user must have at least one line between each other user with whom he wishes to communicate. By definition, there is no sharing of communications facilities in this system. Each user has a separate communication port (e.g., a telephone) to each other user with whom communication is desired, and must organize their



NO RESOURCE CONTENTION

COMMUNICATION CAPACITY LIMITED BY PHYSICAL CHANNEL CHARACTERISTICS

NO RESOURCE SHARING

Figure A-1 -- Dedicated Communication

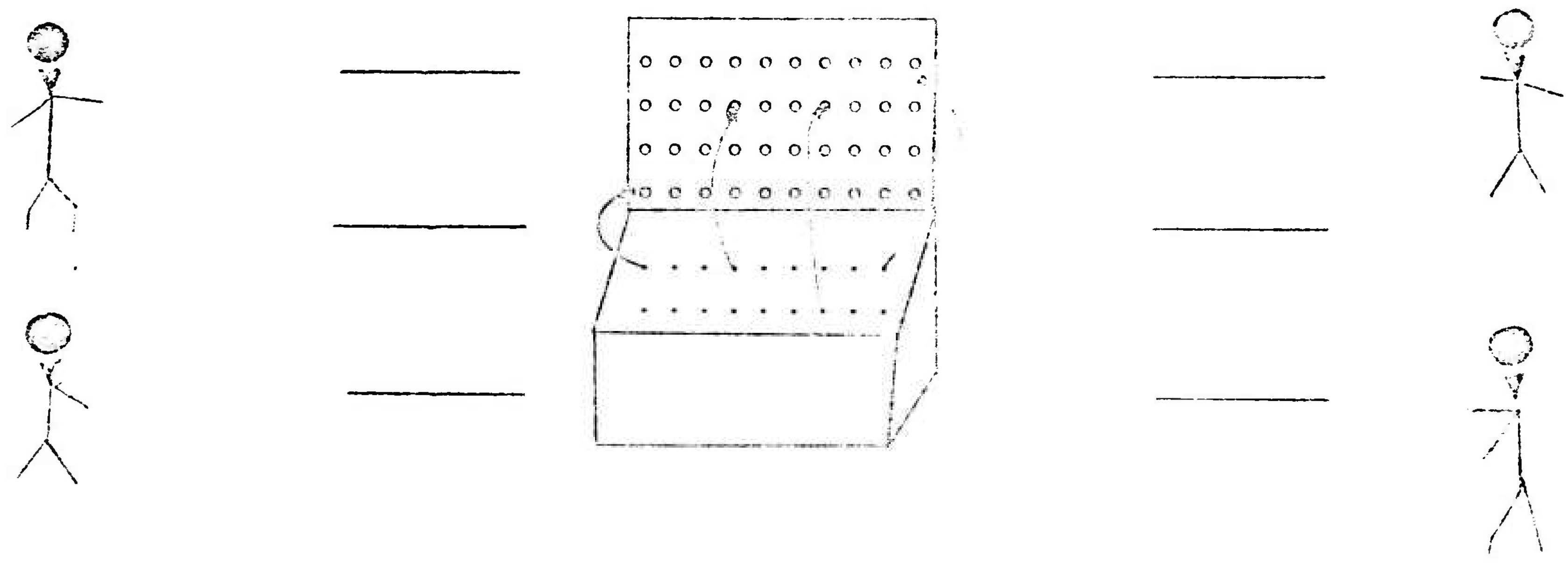
usage. Depending on personal resource organization, each user may perform several simultaneous communications with other users, or alternatively, choose to handle only one communication at a time.

For a satellite communication system, a dedicated line consists of one or more satellites that uniquely support communications between individual information sources and users. The implementation could be a single satellite or, for more extensive coverage, through multiple communication satellites. An entire satellite communication capacity could be dedicated to the single communication or individual channels less than full satellite capacity could be dedicated to the single communication path. In any case, the entire communication path is permanently dedicated to only one pair of users, independent of how the communication path is physically implemented.

3. Circuit Switching

In order to permit the sharing of communication resources among users, a scheme of creating dedicated communications paths as needed is used. In this concept, known as circuit switching, an entire path is allocated to a given transmission, whether used or not. The basic idea, as shown in Figure A-2, is that of a rudimentary telephone system. Whenever a user wishes to communicate with another, a line is established at that time for the communication. In the simplest case, a single switchboard can be used for connecting users, but more general systems can have several switchboards between users. Since communication lines and circuits are shared, there may be contention for communication lines. Consequently, there can be times when the communication will be delayed or even impossible (e.g., holiday telephone calls). In general, circuit switching is useful in situations requiring continuous transmissions over long periods of time.

For a satellite communication system, a circuit switch system is similar to the current usage of single communication satellites. Whenever a communication path is required, it must be established through



CONTENTION FOR CIRCUIT AVAILABILITY

COMMUNICATION CAPABILITY LIMITED BY PHYSICAL CHANNEL CHARACTERISTICS

RESOURCE SHARING BY RESERVATION/ALLOCATION

Figure A-2 -- Circuit Switch Communication

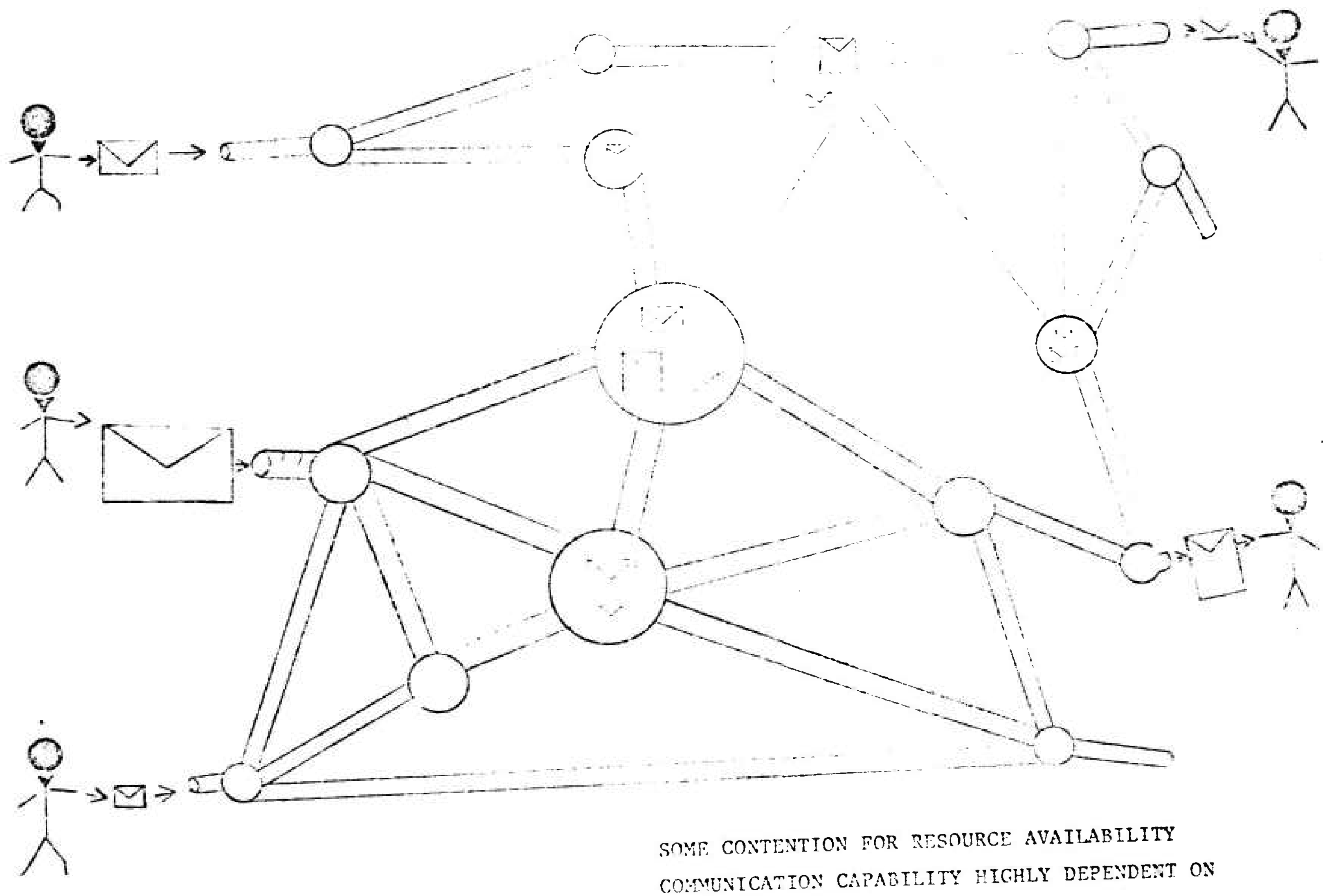
some form of resource allocation. The particular path is not shared with any other user other than multiplexing. When multiple satellites are utilized, a circuit switch system may be much more complex than a dedicated system. This may occur if distinct communication paths can be chosen at the outset of communication.

4. Message Switching

Depending on the user's communications requirements, it is possible to utilize more sophisticated methods for sharing resources. In the network concept known as message switching, only one channel is used at a time for a given transmission. The message travels from its source node to the next node in its path. When the entire message is received at this node, the route to the next node is selected. The message may have to wait in queue for busy channels to clear, so message switching involves store and forward techniques.

To illustrate this concept, Figure A-3 shows communication performed in transmission of fixed messages, such as letters and telegrams. A complete message is transferred from a source to a user as a unit. The message is placed in the system along with an attached destination address. Then, based on the system's routing algorithms, the message is eventually delivered to its destination. There is usually little contention for the communication system port (e.g., the mailbox), but the system's ability to transfer messages is shared and, accordingly, is affected by the characteristics of the message traffic.

Within a satellite communication system, the message switching technique requires processing and memory capacity at each node (e.g., ground station, satellite) along the communication path. The processing is required to determine where next to send a given message along a path to its destination. The memory is required to queue messages that are in transit. Since messages can be of different sizes, there must be sufficient memory onboard each satellite in the network to store at least the



SOME CONTENTION FOR RESOURCE AVAILABILITY

COMMUNICATION CAPABILITY HIGHLY DEPENDENT ON MESSAGE VOLUME

RESOURCE SHARING WITHOUT RESERVATION

Figure A-3 -- Message Switch Communication

largest message size allowed. In addition, a processing scheme must be implemented to handle messages of varying sizes.

5. Packet Switching

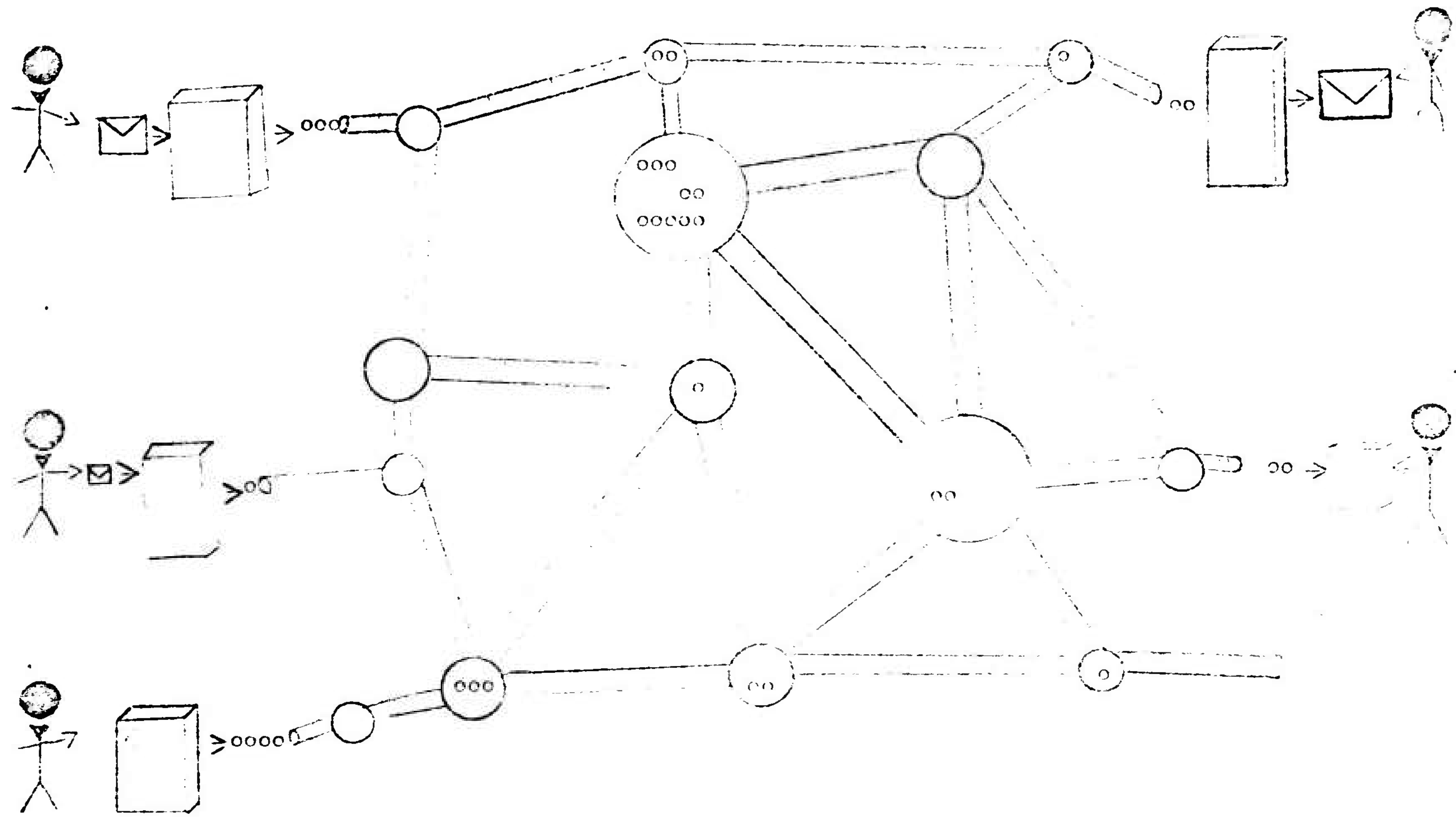
A considerably sophisticated demand multiplexing of communications resources over that of message switching is possible by the network technique known as packet switching. This concept is based on the requirement for the system to simultaneously handle a variety of types of information traffic as well as to effectively exploit the inherent parallelism of multiple interconnection paths between source and user.

In packet switching, individual messages are broken into pieces called packets, each of which has a maximum length. The packets are numbered and addressed and proceed through the network as in message switching. In a distributed packet-switched network, many packets of a given message may be in transmission simultaneously. This "pipelining" can reduce transmission delay appreciably over that of message switching. The reduction may be as large as a factor proportional to the number of packets into which the message is broken.

Such a shared resource communications capability is illustrated in Figure A-4. The basic concept is that information may be broken up into small fixed sizes for communicating in the network. Each packet may be routed to its destination independently, sometimes in much the same manner as in message switching.

The total message is automatically broken up into its component packets on entry to the system and put back together at the destination before delivery to the destination user. This feature allows the packets that make up a message to be routed through the system independently and possibly concurrently.

Within a satellite communication system, packet switched communications requires processing and memory capacity at each node. (e.g., ground



LITTLE CONTENTION FOR RESOURCE AVAILABILITY

COMMUNICATION CAPACITY DEPENDENT ON USER REQUIREMENTS

RESOURCE SHARING WITHOUT RESERVATION

Figure A-4 -- Packet Switch Communication

station or satellite) along the communication path. Like message switched communications, the processing is required to determine the next destination for a packet. However, the memory onboard a satellite need only be a fixed multiple of the packet size. The processing required to maintain the packet queue handles small fixed length packets as opposed to varying sized messages.

6. Comparative Analysis

An important advantage of the store and forward systems (message and packet switching) over circuit switching is that speed, format and code conversions can be accomplished at the network nodes. Complete end-to-end compatibility thus is not required, as is the case with circuit switching.

Another advantage of store and forward systems over circuit switched systems is that in a moderately busy network, a set-up signal may find it difficult to locate a complete path of available channels from source to destination, i.e., the system is "busy" or blocked. With store and forward techniques, only the next channel in the path needs to be available. Packet switching has a further advantage of being able to adaptively select good paths for packets as a function of network congestion.

Besides providing small network delays, packet switching can handle short messages rapidly even though long messages may be in the system at the same time. This results from the fact that all messages are broken down to packet length. Of significant importance, relative to a message switched network, a packet switched network typically has only modest nodal storage requirements because of the fact that all messages are broken down into packets, each of some maximum length (say 1024 bits each).

Both message switching and packet switching involve the use of headers. Because of header overhead, the number of bits transmitted is less for message switching than for packet switching. However, provided the messages are not too long the network delay is less for packet switching because many packets of a given message can be transmitted simultaneously.

For message switching,

Delay $\propto$ Message Length x Number of Hops

An actual delay calculation must also include the transmission delay of each hop.

For packet switching,

Delay $\propto$ (Packet Length x Number of Hops)

+ (Term x Message Length)

+ (Control Signal Delay)

As with message switching, an actual delay calculation must also include the transmission delay of each hop.

Because digital data transmission requirements (both source and user) tend to come in bursts, they lend themselves well to message and packet switching, both of which involve the sharing of transmission resources.

In summary, the use of packet switching is justified in those situations in which transmissions are intermittent, delay must be minimized, and messages may be of considerable length and simultaneous transmission of packets can be accomplished.

APPENDIX B

ADDITIONAL SATELLITE DATA MANAGEMENT CONSIDERATIONS

1. Introduction

In the course of this investigation, a number of issues peripheral to the central focus of the study were developed. These diverse topics considered a variety of necessary technology factors in the effective design of satellite data management algorithms. Such considerations included:

- ARPA Network Time Delay Considerations
- Space-Earth Link Limitations vs. Frequency
- Maximum Possible Interlink Data Transfer Rates
- Satellite Payload Considerations
- Utilization of Transmission Resources
- Effects of Satellite Orbital Parameters
- Motion of Geosynchronous Satellites
- Satellite Station Keeping Requirements for Laser Transmissions
- Characteristics of Satellite Packet Switching Networks

Each of these topics were discussed in technical notes prepared during this study for use in SAMSO technical meetings. These technical issues are felt to be of high interest to the overall data management program. For the convenience of the reader, each of these considerations is abstracted in separate sections of this Appendix.

2. ARPA Network Time Delay Considerations [31]

Response time T is the average time a message takes from its origin to its destination. In the ARPA network, a "short" message corresponds to a single packet of 1008 bits or less. If T_i is the mean delay time for a packet passing through the ith link, then

$$T = \frac{1}{r} \sum_{i=1}^{m} f_i T_i$$

where

r = total traffic rate input to the network from all sources (b/s)
f_i = average flow rate in the i th link (b/s)
M = total number of links

$$T = \frac{1}{r} \sum_{i=1}^{m} \left(\underbrace{\frac{1/\mu}{C_i - f_i} - \frac{1}{C_i \mu}}_{\substack{\text{average time a packet waits at}\\ \text{IMP for link i to become abailable}}} + \underbrace{\frac{1}{C_i \mu'}}_{\substack{\text{time to send packet}\\ \text{of average length } 1/\mu'}} + \underbrace{d_i}_{\text{propagation time}} \right) f_i$$

where

C_i = capacity of link i
i/μ' = average information packet length
i/μ = average packet length in the system, including requests for next messages, header, acknowledgements, and parity check
d_i = propagation delay of link i, seconds

Assuming a relatively homogeneous set of C_i and d_i, no individual term in the expression for delay will dominate the summation until the flow in one channel (e.g., channel i_o) approaches the capacity C_{i_o}. At that point, the term T_{i_o}, and hence T will grow rapidly. The expression for delay is then dominated by one (or more) terms and exhibits a threshold behavior. Prior to this threshold, T remains relatively constant.

The manner in which delay varies with throughput for four cases is shown in Figure B-1, where the letters refer to the following conditions:

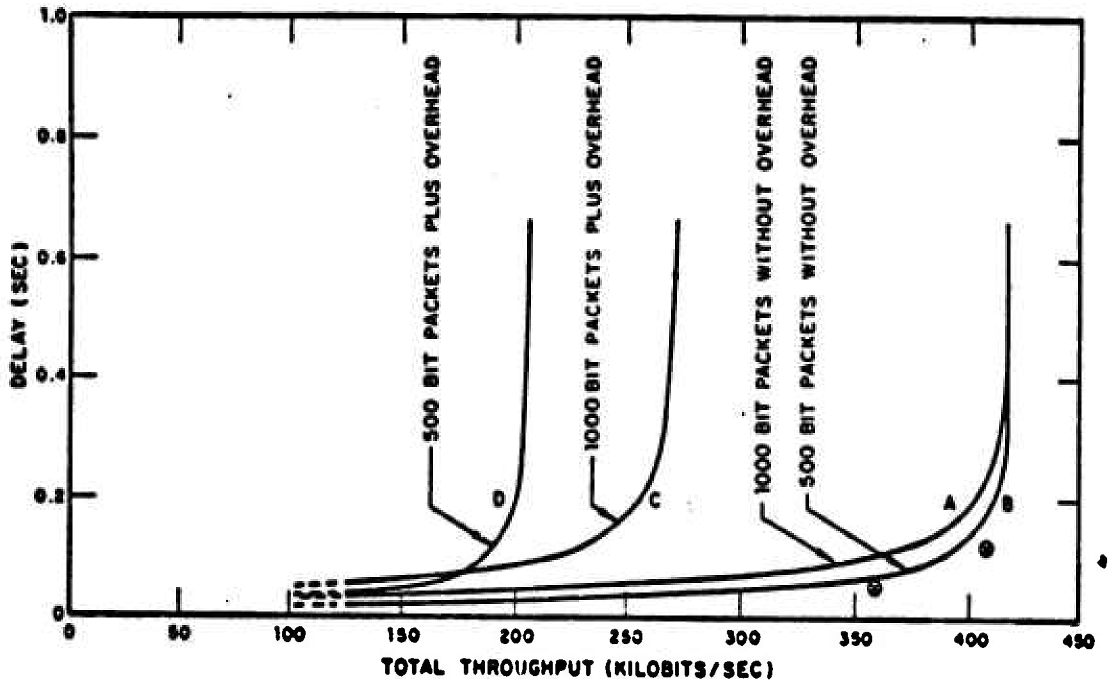


Figure B-1 -- Network Time Delay vs. Total Throughput

A - Fixed 1000 bit packets (overhead ignored)

B - Exponentially distributed variable length packets with average size of 500 bits (overhead ignored)

C - Fixed 1000 bit packets plus overhead of 136 bits/packet and per request for next message and 152 bits per acknowledgement

D - Exponentially distributed variable length packets with average size of 500 bits plus overhead of 136 bits/packet and per request for next message and 152 bits per acknowledgement

The curves were obtained on a 19 node network and on ten nodes of the ARPA net. The x's show the results of a simulation that omitted all network overhead and assumed fixed lengths of 1000 bits for all packets. The curves show that as long as traffic is low enough and the routing adaptive enough to avoid the premature saturation of cutsets (links that connect one group of nodes to all remaining nodes) by guiding traffic along paths with excess capacity, queueing delays are not significant.

A technique developed by the Defense Communications Agency for traffic that is longer than a single packet involves splitting the buffering between the originating and destination nodes and essentially eliminating the segment reassembly process. Short response times are maintained for interactive messages and large bandwidths for long data exchanges. Variable length packets are used, with only the maximum packet length being specified.[51]

Considering header requirements, a maximum length of about 2000 bits was found to be optimum for the line efficiency of typical circuits when the existence of rather poor access circuits is presumed. This contrasts with an optimum packet length for the ARPA-net of about 4000 bits to maximuze throughput, although network efficiency is not compromised significantly for lengths between 1000 and 8000 bits.

3. Space-Earth Link Limitations vs. Frequency

The following section presents an examination of all wavelengths of electromagnetic radiation down to the ultraviolet and establishes the factors that enhance or limit the use of each spectral range for space-earth communication. Pertinent parameters are:

- Attenuation of the medium
- Potential information rates
- Limitations on lasers for satellite-ground transmissions
- Feasibility of launching and intercepting signals efficiently
- Link privacy

A. Attenuation of the Medium

(1) Frequencies Below 3 to 5 MHz

The lowest electromagnetic frequencies (below a "critical frequency" on the order of 3 to 5 MHz) are reflected by the ionosphere back to earth and thus do not warrant consideration for space communication.

(2) High Frequencies (HF)

Between the "critical frequency" and a "maximum usable frequency" (ranging from 10 to 35 MHz) lies a region of the spectrum in which waves vertically incident from the earth upon the ionosphere travel out into space, whereas waves incident at oblique angles are reflected back to the earth. In the lowest frequency portion of this range, only those waves that are almost vertically incident penetrate the ionosphere, whereas in the upper portions of this range, waves at increasingly large angles penetrate into outer space. The variable behavior of this frequency range with time of day, time of year, and the eleven-year sunspot cycle, make it generally unsuitable for reliable space communication.

(3) 35 MHz to 10 GHz

The portion of the spectrum between 35 MHz and 10 GHz is a region of relatively low attenuation between earth and space. In this range, cosmic noise and man-made noise are present at the low end,

but decrease with frequency to a level that does not usually exceed -180 dBW/kHz at 2.0 GHz. This is equivalent to a 78K noise temperature, typical of preamplifiers readily available for these frequencies.

The frequency range between 2 and 10 GHz is heavily used for satellite transmission because of its low noise and low attenuation.

(4) <u>10 to 275 GHz</u>

Above 10 GHz, moisture and other constituents in the atmosphere cause the attenuation to increase with frequency, and to peak at various frequencies. The 10 to 275 GHz region, however, has numerous bands allocated to space communication based upon the presence of transmission windows. With space diversity on the earth, such frequencies should prove usable even during local rainstorms. The allocated frequencies (including broadcasting, exploration, aeronautical and maritime satellites) are as follows (GHz):

11.45	to	12.20
12.50	to	12.75
14.00	to	14.50
17.7	to	22.0
27.5	to	31.1
40.0	to	48.0
50.0	to	52.0
65.0	to	71.0
84.0	to	86.0
92.0	to	101.0
102.0	to	105.0
140.0	to	152.0
190.0	to	200.0
220.0	to	230.0
250.0	to	275.0

Various absorption bands exist between many of the bands listed above. The absorption results from oxygen, water vapor, and other constituents of the atmosphere. Such absorption is not present on intersatellite link paths, however, provided the paths remain above the atmosphere. Consequently, excellent link privacy is afforded. Development at 60 GHz has been done toward the objective of providing private intersatellite links.

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(5) Frequencies Above 275 GHz

Additional windows exist at higher frequencies, which go well into the infrared region.

A general window is found from 10^{12} to 10^{15} Hz (1000 GHz to 1,000,000 GHz). This corresponds to wavelengths of 300 microns down to 0.3 microns, and includes the near infrared, optical, and near ultraviolet ranges. The use of this window is limited by cloud presence, since clouds contain particles whose sizes are comparable to the wavelengths of concern. The advantages of these frequencies are the extremely narrow beam widths possible, thus enhancing link privacy, but demanding fixed or very stable platforms for transmission and reception. Very narrow beam widths also preclude multiple simultaneous relays through single-terminal hardware sets.

Scintillation due to atmospheric turbulence would have little effect on transmissions at wavelengths longer than 8 μm, but shorter wavelengths, especially below 1.0 μm, would be adversely affected, and thus should be considered only for intersatellite links.

B. Potential Information Rates

The potential information rate R of a space to earth or earth to space link is proportional to the bandwidth B of the link and the number of modulation levels N used. This can be expressed as follows, allowing 15% bandwidth for waveform recovery and guard bands:

$$R = \frac{N \times B}{2 \times 1.15} = 0.435 \text{ NB b/s}$$

where B is the available bandwidth in Hz

Thus a simple two level (0,1) system occupying a 1 MHz bandwidth can transmit information at an 870 kb/s rate. Correspondingly, a quadrature amplitude modulation/phase-shift keyed (QAM/PSK) system (N = 8) capable of transmitting 9600 b/s requires a bandwidth of 2760 Hz, and can function in a 300 to 3000 Hz voice bandwidth.

The information rate on a channel can be made arbitrarily large in the absence of channel noise and phase jitter, both of which act against the use of N values appreciably higher than 8 at the present time. In the frequency bands above 2.0 GHz, both channel noise and jitter are produced primarily by equipment, so the following development directions are indicated:

- Transmission equipment with minimum possible phase jitter (substantially less than $\pm 20^{\circ}$) to allow increases in the number of levels substantially beyond 8.
- Transmission equipment capable of improved performance over against equipment noise. This means:
  - More efficient transmitters for increased power output from a given power input. Present efficiencies are approximately as follows:

12 GHz:	50% (developmental)
94 GHz:	25%
10.6μ:	3%
0.53μ:	0.1%

  - Receivers with improved noise levels. Noise factors of present receivers are as follows:

12 GHz:	3.6
94 GHz:	7.0
10.6μ:	2.0
0.53μ:	2.0

- Transmission equipment capable of being modulated and demodulated at rates substantially higher than the present 500 MHz bandwidths of which traveling wave tubes are capable. With increased bandwidths, development is also needed on bit stream serializers and synchronizers capable of multiplexing and de-multiplexing bit streams well in excess of 1 G b/s.

C. Limitations on Lasers for Ground-Satellite Transmission

The ease with which laser energy can be concentrated into narrow beams makes their use on satellite links readily possible at low power levels. For example, a 3 watt, 10.6 μm laser and a 0.2 W, 0.53 μm laser each can operate over 40,000 km distances at a 1 GHz bandwidth and provide adequate signal-to-noise ratio for bit error rates on the order of 10^{-6}.

Such lasers, if ground based, would be operated only when the cloud cover would not cause appreciable attenuation and scattering. Even if 33% of the energy were scattered back to the region around the transmitter, or if 33% of the energy were to be lost in sidelobes, this would represent only one watt. Since laser transmitter beams can be aimed accurately into space, and can be provided with suitable shrouds to prevent sidelobe radiation on their surroundings, no danger to operators or other personnel in the vicinity of a laser transmitter should exist.[17]

D. Feasibility of Launching and Intercepting Signals Efficiently

Signals can be transmitted and received at all electromagnetic frequencies, but with varying degrees of efficiency. Only limited antenna development has been done at frequencies above 20 GHz because extensive applications for the use of these frequencies have only recently been formulated. Present antenna efficiencies of 25 to 40% should be improved to the 65 to 80% range.

In the optical and near-optical range, high efficiency (e.g., 30%) sources are available in the 10.6 μm wavelength region, whereas the use of the 0.5 μm region allows simple photo-multipliers to be used for reception and doubled Nd:YAG lasers to be used for transmission.

E. Link Privacy

Link privacy can be achieved in three ways:

- The use of extremely narrow beam widths, rendering outside interception difficult.
- Transmission behind a propagation barrier.
- The use of special coding techniques.

Narrow beam widths are most readily achievable at the highest frequencies, and argue strongly for laser and infrared transmission, providing adequate platform and beam stabilization can be obtained.

Transmission behind a propogation barrier is feasible above the atmosphere on intersatellite links, and can be done most readily in the atmosphere absorption bands.

Special coding techniques have been developed extensively for military communication systems; in general, all transmissions are on an encrypted basis. The continued use of such techniques is assumed.

4. Maximum Possible Interlink Data Transfer Rates

This section presents an analysis of the maximum interlink data transfer rates possible based upon two technologies:

(1) Linear beam tubes and solid state devices

(2) Lasers

In each case the total data flow to/from a satellite can be obtained by multiplying the resulting value by 2 for polarization diversity, and by n for the number of separate beams into which and from which energy can be sent. This assumes the use of 2n transponders on board each satellite.

A. Linear Beam Tubes and Solid State Devices

The maximum data flow via a satellite link now possible with linear beam tubes and solid state devices can be predicted from their bandwidth capabilities and the Shannon limit, which involves the link power budget as well. The NASA forecast estimates that powers up to 100 watts will be available at frequencies up to 90 GHz from linear beam tubes by the year 2000, as portrayed in Figure B-2.[37]

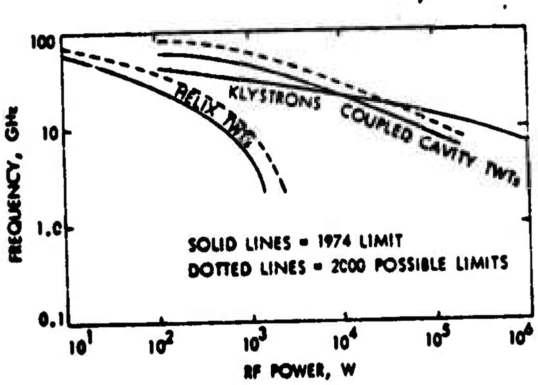


Figure B-2 -- Maximum Power-Frequency Characteristics of Linear Beam Tubes

Staff studies at Hughes Aircraft Co. have indicated the feasibility of 2 GHz bandwidth traveling wave tubes (TWT's) from 2 to 100 GHz at power levels up to 100 to 200 watts and efficiencies of 30% at 2 GHz, 50% at 12 GHz, and 20 to 25% at 85 GHz. These are helix TWT's below 12 GHz and coupled cavity TWT's above 12 GHz operating as Class C amplifiers.

Solid state devices by comparison appear to offer less power at a given frequency than do linear beam tubes, as indicated by Figure B-3.

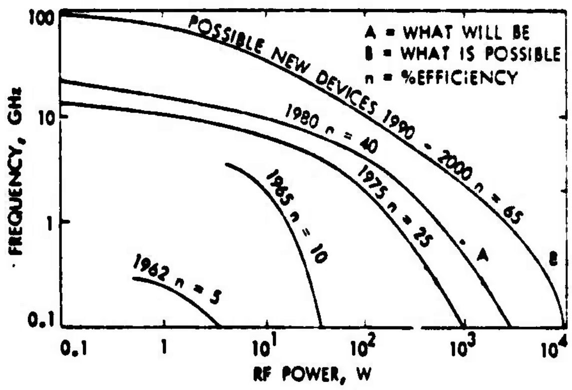


Figure B-3 -- Solid-State Power Frequency Characteristics

Consequently, linear beam tubes are assumed for the remainder of this discussion.

The next question is: What data flow can be transmitted over the available bandwidth? The answer depends on the signal-to-noise power density ratio E_b/N_o. The extent to which the Shannon limit is approached depends upon the modulation system used, as indicated in Figure B-4.[24]

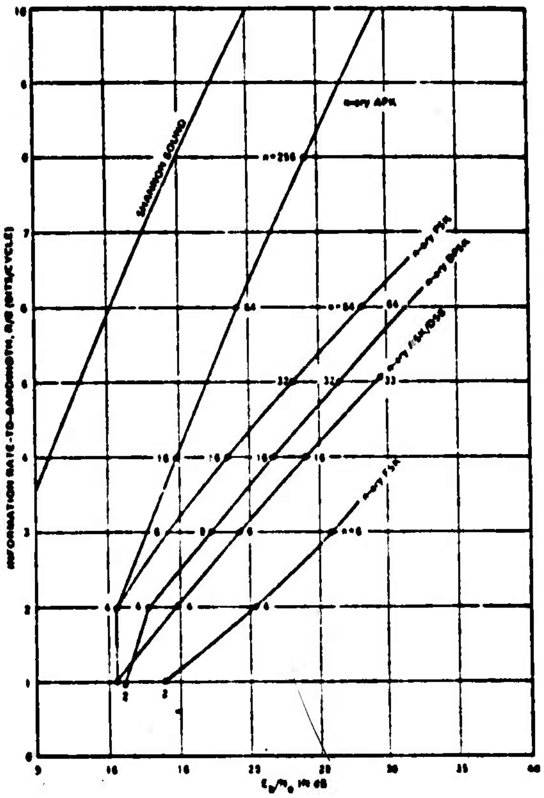


Figure B-4 -- Comparison of Digital Modulation Systems Based on Average Power

In this figure, FSK is frequency shift keying, ASK is amplitude shift keying, PSK is phase shift keying, DPSK is differential phase shift keying, and APK is amplitude phase keying.

The question logically arises: What E_b/No can be obtained between a geosynchronous satellite and a point on earth over a 2000 MHz bandwidth?

Assume a 40,000 kw slant range to the satellite and good weather conditions, rendering atmospheric attenuation negligible. The link budget, assuming limiting antenna gains of 70 dB, 10 watt transmitters, and 12 K masers at the receivers, then is as follows near the highest frequency for which development studies have been done (90 GHz):

Transmitting power	10 dBW
Transmitting antenna gain (maximum feasible)	70 dB (4.6 meter diameter)
Space loss, 40,000 km path	-223.6 dB
Receiving antenna gain	70 dB
Received power	-63.6 dBW
kTB	-128.26 dBW
E_b/No	54.6 dB

Even allowing 14.6 dB for atmospheric attenuation and failure of various digital modulation systems to meet the Shannon limit (x 10 for E_b/No = 20 dB; x 18 for E_b/No = 40 dB), a data rate of 2000 x 10^6 = 3.6 x 10^{10} b/s can readily be forecast for such a link, or a total data flow of 2n x 3.6 x 10^{10} b/s per satellite. Since 2 n parallel data channels are thus provided, the serializers and synchronizers need only operate at 36 Gb/s in each channel. Rates one third this amount may be achievable by the early 1990's based upon the types of technology extensions being forecast in connection with lasers (see next section).

Based upon extensions of the present technology of large unfurlable multi-beam reflectors in space, as developed in the ATS-6 and similar programs, one can readily visualize a cluster of four 12-beam antennas, for a total of 48 spot beams, each capable of dual polarization. This means that 96 parallel channels, each operating at 12 Gb/s, could be provided in each satellite, for a total data flow of 1.15 x 10^{12} b/s per satellite in the early 1990's, and three times that amount with more rapid digital circuits.

A comparable bandwidth is possible at lower carrier frequencies, based upon octave band tube development being done at Hughes, which has experimental octave band tubes covering 2 to 4 GHz.

The link budget at 2 GHz, assuming 4.6 meter diameter antennas as before (maximum usable size at 90 GHz), 10 watt transmitters and 2 K masers at the receivers then is as follows:

Transmitter power	10 dBW
Transmitting antenna gain	37 dB
Space loss, 40,000 km path	-190.6 dB
Receiving antenna gain	37 dB
Received power	-106.6 dBW
KTB	-138.26 dBW
E_b/No	31.6 dB

The assumed antenna sizes could be increased substantially to bring the E_b/No value back up to that obtained for the 90 GHz system, but substantially greater sizes generate questions about deployable antenna system development feasibility by the early 1990's to 2000. On the other hand, the 2-4 GHz system is not greatly affected by weather but interference to and from existing services in this band could be a serious problem.

B. Lasers

The maximum data flow via a satellite link that is possible with lasers is based upon the same factors that limit the per channel data flow using linear beam tubes and solid state devices. The limitation is that of the data serializers and synchronizers. Circuits for the 1 Gb/s Nd:YAG laser developed under contract to the Air Force have a 300 psec. response time. In the absence of expected breakthroughs the response time can be reduced at the expense of additional power consumption, i.e., the response time can be cut in half by doubling the power consumption.

Forecasts for laser data rates are as follows:

Year	Data Rate	
1976	1 Gb/s	(available; to be flight tested in 1979)
1980	3 Gb/s	forecast
1986	10 Gb/s	forecast

C. Discussion

The factors affecting the ultimate data transfer rate through a satellite are the following:

- Number of transponders
- Bandwidth per transponder
- Modulation system
- Signal to noise power density ratio
- Use of polarization diversity

The choice between linear beam tubes, solid state devices and lasers is not a fundamental one because the bandwidth per transponder is limited more by the modulation circuitry than the transponder type per se. However, the maximum number of transponders per satellite is a function of transponder efficiency for a given available power level.

By the year 2000, a total data flow per satellite of 3.5×10^{12} b/s should be possible.

5. Satellite Payload Considerations

The need for special data management measures is directly related to the volume of data to be transmitted from source to user, relative to the capabilities of the transmission medium to handle such data volumes. This makes it appropriate to examine the potential payload size, weight and power availability on board both synchronous and earth-orbiting satellites of the 1980-1990 time frame and beyond. Such resources then can be allocated to communications transponders, data storage media, on-board switching matrices and processing capability.

A. Synchronous Orbit Payloads

Projections for synchronous orbit start with the present ATS-6,[23] which was launched on May 31, 1974, and provides 300 watts to a 1000 lb. communications payload that occupies 75 cubic feet. Overall spacecraft power is 500 watts; weight is 3000 lb., and volume, exclusive of the solar array and the reflector, is about 120 cubic feet. The differences

are for structure, attitude control thermal control power subsystem, telemetrics and command and other housekeeping-type functions. All of these functions are necessary to the operation of the spacecraft, but constitute an "overhead" that cannot be allocated to the actual communications payload. The projections made in the remainder of this section all allow for an appropriate "overhead" and thus are lower than overall published figures.

Projections for synchronous orbit for the 1985 to 1990 time frame are based on the use of the shuttle/interim upper stage (IUS), which can place 5000 lb. into orbit, of which an estimated 3000 lb. might be working payload. Based upon a spacecraft sized 15 feet in diameter by 35 feet in length and allowing one-third for structure, power and other housekeeping functions, the space could be 4100 cubic feet. The 35 foot length would allow the deployment of at least four solar arrays (maximum of eight) of the type now in use on the Communications Technology Satellite. These arrays are in pairs, each member of a pair being 256 inches long and 51.6 inches wide. A pair produces an initial power of 1260 watts. Allowance for housekeeping and degradation over a seven year lifetime results in 600 watts per pair, or 2400 watts from four pairs.[15]

An alternative to a single spacecraft, as implied above, would be multiple spacecraft whose total size and weight could be accomodated by the Shuttle/IUS vehicle. A trade-off to determine what number of spacecraft should be launched from a shuttle/IUS remains to be made. For simplicity, only one is assumed in this discussion.

B. Near Earth Orbit Payloads

Projections for earth orbiting satellites for the 1985 to 1990 time frame are based upon several considerations. First, there are no firm plans for a shuttle launch into polar orbit, which is a useful orbit for many types of sensor missions. (Results of studies relative to such a launch would be useful, as well as additional information on shuttle launch of satellites into other low earth orbits.) Available options are:

- Use of the shuttle itself (150 mile altitude)
- Use of the Delta 2914, which can put a 5200 lb. satellite into near earth orbit. The size of spacecraft which can be accommodated in the Delta 2914 housing is at least the size of the CTS, which can provide an estimated 600 watts to its working payload. Maximum on-board space needs to be determined, but space on the order of 50 cubic feet probably could be obtained.[14]

C. Working Payload Factors

The working payload referred to in the previous paragraphs consists of the following types of components in the satellite nodes under consideration:

(1) Video transponders - A 34 MHz bandwidth transponder currently weighs about 7 lb. and draws 45 watts. Size totals about 2" x 6" x 10", or 120 cu. in. each.

(2) Data storage - Data storage is required both for processing and for the communications store-and-forward function. Ferrite core memories (1975-1980 time frame) weigh 2×10^{-5} lb/bit and occupy 6×10^{-4} cu. in./bit. Power requirements are 1.8×10^{-5} watts standby and 2.8×10^{-4} watts operating. CMOS/SOS memories (1985-1990 time frame) weigh 5×10^{-6} lb/bit and occupy 3.5×10^{-5} cu. in./bit. Power requirements are 5×10^{-6} watt/bit (1985) to 5×10^{-7} watt/bit (1990).[48]

6. Utilization of Transmission Resources

For purposes of this discussion, it is assumed that the satellite data rate requirement to be achieved ranges from 10^6 to 2.5×10^{11} b/s. It then may be asked: How can a geostationary satellite's resources (space, weight, power) best be allocated to handle such data rates?

As a representative set of transmission resources for illustrative purposes, assume the use of 24 transponders, each of 34 MHz bandwidth, and each capable of a data flow of 2 b/s per baud. Then these transponders will occupy 816 MHz of bandwidth if frequency reuse techniques (orthogonal

polarization and multiple exclusive spot beams) are not employed. Assuming the availability of this bandwidth, the total data flow through the transponders is $24 \times 34 \times 10^6 \times 2 = 1.632 \times 10^9$ b/s. They require a total of $45 \times 24 = 1080$ watts and weigh 168 lb. Assuming a packing factor of 0.7, they will occupy 4114 cu. in. or 2.4 cu. ft.

Assume the use of processing capability that can provide data compression of 4:1. Then the maximum input data rate that can be handled without switching to another satellite or the use of store and forward techniques is $4 \times 1.6 \times 10^9$ b/s $= 6.5 \times 10^9$ b/s. However, the maximum possible input data rate of 2.5×10^{11} is 38.3 times thus great.

For data rates above 6.5×10^9 b/s, a signal may be sent to the source, asking it to send the data in parallel streams, dividing it among 6 satellites. This still means a maximum data rate that is 6.38 times too great for any one satellite.

At this point, if the duration of the 2.5×10^{11} b/s stream is short enough, on-board storage may be used to hold data queues in the satellites. For example, using CMOS/SOS memories at 5×10^{-6} lb/bit, 3.5×10^{-5} cu. in./bit, and 5×10^{-7} watts/bit, the estimated maximum number of bits that can be stored is $\approx 10^{10}$ bits. The amount requiring storage is:

$$\frac{2.5 \times 10^{11} \text{ b/s}}{6 \text{ satellites} \times 4 \text{ (compression factor)}} - 1.6 \times 10^9 \text{ b/s} = 2.11 \times 10^{11} \text{ b/s}$$

Thus the length of time during which such a queue can develop is $\approx$ 50 msec. The foregoing discussion is illustrated graphically in Figure B-5.

The practicallity of the foregoing hypothetical situation is limited by the maximum rate at which serializers and synchronizers can operate. To date, such devices capable of operation at 10^9 baud and above, as implied by the above example, are not available.

The foregoing situation also points out the necessity of examining the time duration over which data at a 2.5×10^{11} b/s rate would be

Assumption:

- 6 nodes capable of parallel transmission, placed in geostationary orbit by shuttle/IUS
- CMOS/SOS storage

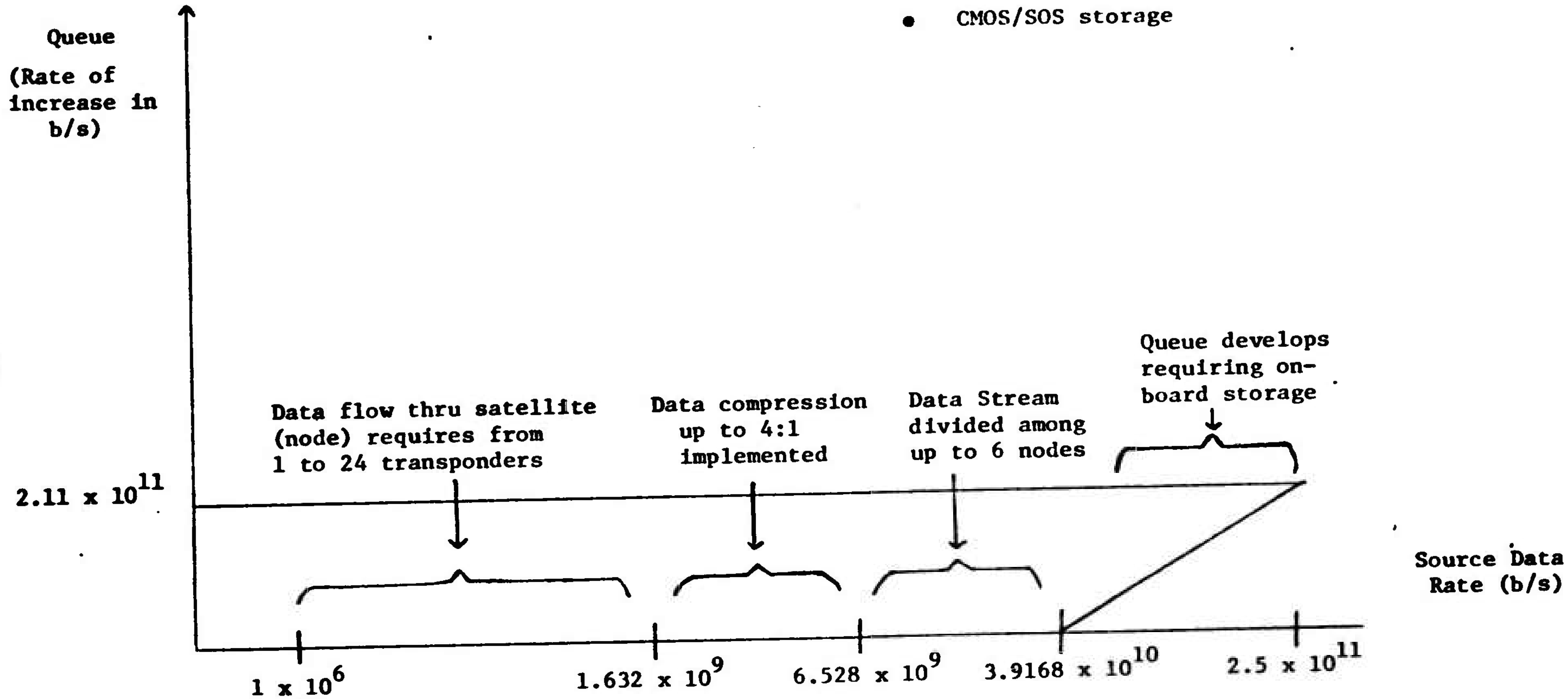


Figure B-5 -- Satellite Data Handling Capability

entering the system. For example, once a given image has been obtained, it may be necessary simply to update that image by the use of moving target indication, or by looking at differences that develop from one sensor pass over the image area to the next pass.

Various assumptions can be made with respect to the amount of on-board storage that will be devoted to queues. A maximum queue length might be based upon allocating 2000 lb and 200 watts to storage. Using the CMOS/SOS memory estimates for 1990, a total of 4×10^8 bits could be stored in queue. Such a store would occupy 14,000 cu. in., or 8.1 cu. ft. Assuming data compression to be 2.5 bits/pel, a total of 1.6×10^8 pels could be stored. A high resolution image of 4:3 aspect ratio might contain 1200 x 900 pels, or 1.08×10^6 pels (2.7×10^6 bits). Thus a total of 148 such images could be stored.

In general, the queue length, Q, can be related to the image rate and resolution, the output and input bit rates, and the input duration as follows:

$$Q = \left[PR-(b/s)_{out}T_{on}\right] = (\Delta b)\ T_{on}$$

P = image resolution bits/image

R = image rate, image/sec.

Δb = input rate less output rate, i.e., $(b/s)_{in} - (b/s)_{out}$, assumed

T_{on} = duration of input, sec.

To avoid exceeding a maximum queue length, Q_{max}, the on time, T_{on}, must be followed by an off time, T_{off}, such that:

$$T_{off} = \left[T_{on}\ \ (b/s)_{in}/(b/s)_{out}\right] = \frac{Q_{max}}{(\Delta b)}\ \left[(b/s_{in}/(b/s)_{out}\right]$$

The bit rates can be related to the transmission bandwidth assuming quadrature phase shift keying (QPSK) yielding 2 b/s per baud and the transmission channel can be assumed to have a nominal width of 1.15 Hz/baud. Therefore BW = 0.575 (Δb), where ΔBW is the input bandwidth, Hz, less the output bandwidth, Hz. This leads to the following relationship:

$$Q = 1.739 \times 10^6 \, (\Delta BW)_{MHz} \, T_{on}$$

The term P, bits/picture, is the actual quantity to be transmitted, assumed to be the uncompressed value. Data compressors can operate at speeds in excess of 10^8 b/s; therefore, for such rates, the compresses value could be used, with compression being done before the data enters the queue. However, inputs in excess of 10^9 b/s will probably have to be compressed after data enters the queue.[35]

Figure B-6 is a plot of this relationship, rearranged to show $(\Delta BW)_{MHz}$ as follows:

$$(\Delta BW)_{MHz} = \frac{Q}{1.739 \times 10^6 \, T_{on}}$$

This figure, in effect, shows the use of the queue in providing a continuous low rate bit stream from a discontinuous high rate bit stream. It also shows that with a sufficiently great queue length, the output bandwidth apparently drops to zero! This merely means that the data store has not been filled, and can take additional input before output is required.

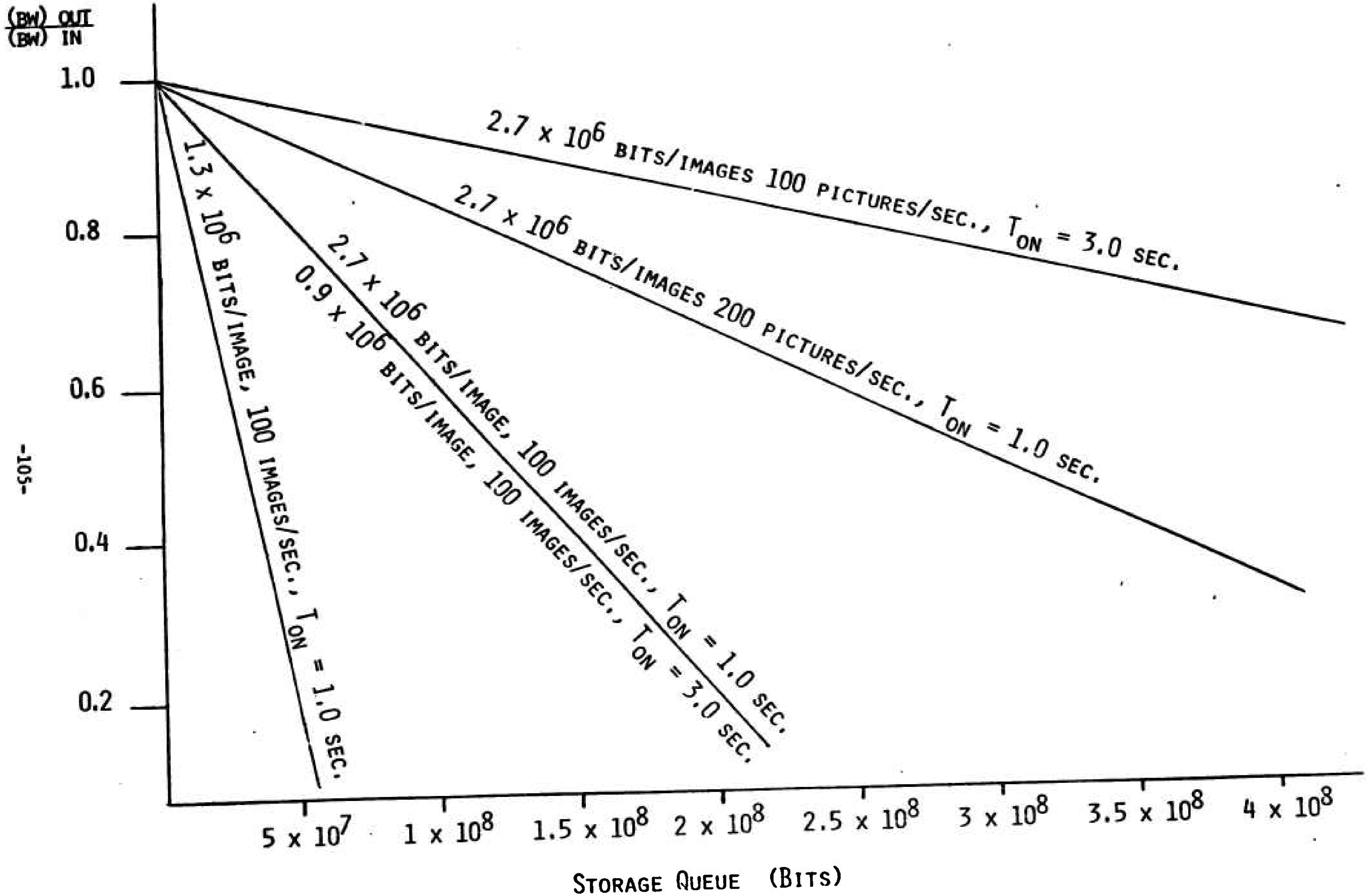


FIGURE B-6 -- BANDWIDTH REDUCTION VS. QUEUE LENGTH

7. Effects of Satellite Orbital Parameters

The development of practical satellite data management technology requires consideration of two factors relating to the relative motion among the earth-based and satellite-based nodes of a multi-satellite system. These are:

- Variable velocity considerations
- Variable angular position considerations

Five cases are presented to illustrate these factors.

A. Variable Velocity (Doppler Frequency Shift)

Synchronous satellites are not truly stationary with respect to the earth. Each satellite, because of its orbital inclination (direction of travel relative to the equator), goes through a daily figure 8 pattern. Any Doppler shift resulting from such motion, however, is small compared with the Doppler shifts between geostationary and low-earth orbiting satellites, as well as between low earth orbiting satellites and the ground. The following computations show that such Doppler shifts do not present a problem, because the resulting frequency shifts are on the order of one to twenty-five (25) parts per million. One part per million is comparable to the frequency shift that occurs with good crystal-controlled oscillators typically used for transmitter and receiver frequency control. Cases in which the 25 parts per million shift occurs can be handled by suitable guard bands between channels. Efficient spectrum utilization can be achieved by keeping channel bandwidths as large as possible.

Case I: Polar Orbiter to Polar Orbiter, Doppler

Assume two satellites are in eccentric polar orbits, each with a perigee of 300 nautical miles and an apogee of 700 nautical miles. One is at an apogee (minimum velocity) when the other is at its perigee (maximum velocity). The two are assumed to be within line of sight of one another at this time.

Satellite velocity, v, is calculated by: $v = \sqrt{\frac{\mu}{r}}$ meters/sec.

where $\mu = 3.991 \times 10^{14}$

r = distance from center of earth = $r_e + r_o$

r_e = earth's radius = 6.378×10^6 m.

r_o = satellite distance above the surface of the earth

At 300 n.mi = 345.2 mi. = 555.6 km = 5.556×10^5 m, $r = 6.9339 \times 10^6$ and $v = 7.5868 \times 10^3$ m/sec.

At 700 n.mi. = 805.5 mi. = 1296.4×10^6 m., $r = 7.6766 \times 10^6$ m and $v = 7.2114 \times 10^3$ m/sec.

Thus $\Delta V = V_{300} - V_{700} = 3.75 \times 10^2$ m/sec. at a carrier frequency of 18 GHz, for example, the wavelength is $c/f = 3 \times 10^8/18 \times 10^9 = 1.666 \times 10^{-2}$m and the Doppler shift is $\Delta f = \Delta V/\lambda = 2.2528 \times 10^4$ Hz $\approx$ 22.5 KHz. Thus the Doppler shift is 1.25 KHz/GHz, or 1.25 ppm.

Case II: Polar Orbiter to Earth or Geostationary Satellite, Doppler

Assume one of the above polar orbiting satellites is in communication with a station at a fixed point relative to the earth. This fixed point may be on the earth's surface or it may be at a geostationary satellite. In either event, the relative velocity will be maximum when the geometry is such that the polar orbiter is moving directly toward or directly away from the fixed point. In either case,

$$\Delta V = V_{300} = 7.5868 \times 10^3 \text{ m/sec.}$$

$\Delta f = 7.5868 \times 10^3/1.666 \times 10^{-2} = 455$ KHz. Thus the Doppler shift is 25.27 KHz/GHz or 25.27 ppm.

B. Variable Angular Positions (Antenna Pointing Requirements)

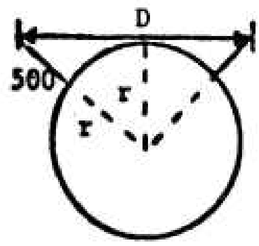
Near earth orbiting satellites, as described in the previous section, have beam steering requirements (if using narrow beam antennas) as indicated in the following cases:

Case 3: Polar Orbiter to Polar Orbiter, Angular Rate

The maximum distance between two polar orbiters at a 500 n. mi. height (575.4 miles) is 4423.5 miles. If the apogee is 700 n.mi., then

Δh = 200 n.mi. = 230.2 miles and

$$\emptyset_{max} - \emptyset_o = \tan^{-1}\frac{230.2}{4423.5} = 2.98^\circ$$



Thus $\Delta\emptyset = \pm\ 2.98^\circ$ maximum.

Since the time from apogee to perigee is 45 minutes for a 500 n.mi. orbit, the maximum angular rate is:

$$\Delta\emptyset/t = \pm\ 2.98^\circ/0.75 \text{ hr.} = \pm\ 3.97^\circ/\text{hr.}$$

Case 4: Polar Orbiter to Geostationary Satellite, Angular Rate

At a 500 n.mi. altitude, the polar orbiter is 4538.6 miles from the center of the earth, while the geostationary satellite is 26263.2 miles from the center of the earth.

$$\theta_{max} - \theta_o = \tan^{-1}\frac{4538.6}{26263.2} = 9.8^\circ$$

The maximum angular rate is approximately $9.8^\circ/0.75 = 13.1^\circ$/hr.

Such rates as indicated in Cases 3 and 4 are very well within the capabilities of steerable beam antennas.

Case 5: Polar Orbiter to Ground Angular Rate

This case represents the highest required angular rate. At a 300 n.mi. altitude $V = 7.5868 \times 10^3$ m/sec., while the altitude is 5.556×10^5 m. Thus

$$\Delta\emptyset/t = 7.5868 \times 10^3/5.556 \times 10^5 = 1.365 \times 10^{-2} \text{ rad/sec.}$$

$$= 0.782^\circ/\text{sec.} = 46.9^\circ/\text{min.}$$

This is a much higher rate, but still achievable by on board steerable antennas.

8. Motion of Geosynchronous Satellites

An earth-orbiting satellite is said to have an "inclination" which is the angle which the projection of its orbit on the surface of the earth makes with the equator. For a "polar orbiting" satellite, this angle is 90°, or nearly so, while for a "geosynchronous" satellite, the angle is 0°, or nearly so.

"Orbital drift" may cause a geosynchronous satellite to change its position slightly. The combination of non-zero inclination (caused by slight errors in orbital injection) and orbital drift result in satellite motion that resembles a figure 8 in its station over the equator. Orbital corrections can be implemented by commands to the spacecraft's control system. Such corrections result in the use of on-board power or fuel, however, so most geosynchronous satellites are allowed to drift to some extent. The Radio Regulations, however, "require all satellites to be maintained within ± 1° of the longitude of their nominal position if this is necessary to prevent unacceptable interference in any other satellite network. They urge that efforts should be made to develop spacecraft and control facilities to achieve a capability of maintaining their positions at least within ± 0.5° of the longitude of their nominal position." Furthermore, the use of very narrow beam lasers calls for the most stable satellites possible if tracking complexities are to be minimized.[28]

The factors that tend to produce satellite attitude change are largely related to on-board motions such as relay openings and closures, torques from motor shaft rotations in tracking sensors, and thermal changes (expansions and contractions) resulting from differing sun angles on the spacecraft as well as differing power dissipations on board as systems are switched on and off. Minute variations in the earth's gravitational attraction also can have an effect on satellite orbital drift. Since one major factor that limits satellite lifetime is the amount of propellant it has for attitude control, it follows that a mechanically "quiet" satellite should be capable of longer lifetime than one requiring

frequent orbital adjustments because of on-board torque variations.

Development directions for the "quiet" satellite are the following:

- Eliminate the use of electro-mechanical motions on board the satellite, except for those actually required for attitude adjustment. This means full use of solid-state controls and application of the "phased array" principal to all antennas and sensors.
- Minimize the variation of electrical power utilization so that thermal gradients remain as constant as possible within the spacecraft as system functions change. This may involve the use of dummy loads in very close proximity to the real loads they replace.

Even a perfectly "quiet" satellite would be subject to orbital drift from external forces, i.e., small gravitational variations. Compensation for such external variations can only be accomplished by the use of on board systems. The most efficient methods, in terms on board power or fuel consumption, therefore, should be sought.

Although a high degree of attitude and orbit stability is desired for laser transmissions, both intersatellite and earth to satellite, the value of a highly stable orbit has been shown for microwave transmission as well, thus giving impetus to ongoing research in the field of satellite attitude and orbit stabilization.

9. Satellite Station Keeping Requirements for Laser Transmission

The transmitted beam width of a laser is given by the expression

$$\theta_T = \frac{4\lambda}{\pi D_T} = \frac{4 \times 10.6 \times 10^{-6}}{3.14 \times 0.5} = 2.70 \times 10^{-5} \text{ radians} = 0.00154^{\circ}$$

Since this is much less than 0.2°, tracking becomes even more important. Fortunately, the variations are slow, a complete period requiring one day. This simplifies the tracking system requirements.

Polar and other near-earth orbiters will clearly require tracking systems regardless of aperture size and wavelength.

The use of smaller diameters and longer wavelength systems than those of the first example (synchronous to synchronous intersatellite link) may eliminate the tracking requirement on such systems.

All combinations require acquisition systems. The receiver generally performs an X-Y raster scan with the transmitter beam broadened. Dual scan acquisition has been reported in the literature.[38]

Conclusion: Improvements in satellite stationkeeping accuracy will reduce tracking requirements in the case of synchronous satellites. Tracking is a firm requirement for all near earth orbiters. Acquisition systems must be provided for all intersatellite links as well as for the earth to satellite path except for "global" coverage beams.

10. Characteristics of Satellite Packet Switching Networks

A satellite channel is characterized by its propagation delay (0.24 to 0.27 s for a geosynchronous satellite) and relatively broad bandwidth (e.g., 50 kHz or more). The satellite transponder can retransmit to earth in a broadcast mode all signals that reach it, thus providing automatic acknowledgement. Other features of satellite channels are their invulnerability to unfriendly forces along the path, their access capability to terrestrial communication channels, and the fact that their operation is essentially independent of terminal separation.

The use of packet switching via satellite implies that the conditions for its use (see (discussed in Appendix A, "Basic Network Concepts") have been established and that random access to the full capacity of the satellite channel is provided. The satellite provides a high capacity channel with a fixed propagation delay that is large compared to the packet transmission time. Each user forms his packet and then bursts it out rapidly on the channel at full capacity. Many users operating in this manner thus automatically multiplex their transmissions on a demand basis. The satellite repeats whatever it receives (on a frequency different from the up link frequency); this broadcasted transmission can be heard by every user of the system.

Each user picks out packets addressed only to itself.

A special property of satellite packet switching is that a user can listen to his own transmission as it returns from the satellite.

An important requirement of a satellite switching network is control of time allocations so that two or more transmissions do not coincide or overlap, thus interfering with one another. It is assumed that the senders are geographically separate from one another, and thus one is unable to know when another is sending, except for information sent via the satellite channel. The problem, therefore, requires a decentralized approach. Three such approaches are known as the Aloha, the slotted Aloha, and the reservation system.[51]

In the pure Aloha system, each sender transmits any time he desires, and then listens for his transmission from the satellite to make certain that no interference occurred. If all senders, however, were to retransmit immediately upon hearing a conflict, they are sure to conflict again, so a random retransmission delay is needed to spread the conflicting packets over time.

In the slotted Aloha system, time is slotted into segments whose duration is exactly equal to the transmission time of a single packet. Each sender is allowed to transmit only at the beginning of a time slot, with time referenced to the satellite. This system provides an improvement in efficiency over the pure Aloha system because interferences are now restricted to a single slot duration.

The reservation system is one in which channel usage is scheduled on a fixed or demand basis for specific senders' transmissions.

APPENDIX C

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)
As part of an ongoing Space and Missile Systems Organization (SAMSO) research and development program into advanced space communications networks ~~to~~ It support projected Air Force missions through the year 2000, several studies have been performed to investigate emerging issues in the design of such networks. This final report presents the results of a study to consider one specific issue--that of the design of data management algorithms to optimize performance measures and resource allocations within network and user demand constraints. Included ~~in this study~~ are considerations of message distribution

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modes (e.g., packet switching algorithms), information control (e.g., flow control and routing algorithms) and multiple access techniques.

In the context of this study, data management algorithms consist of all the rules which govern information flow within an envisioned multiple-satellite multiple-mission space communications network. Such data management algorithms permit the orderly interaction of information sources, intelligent satellite nodes which form the communications network, and the information users.

A generalized satellite-based information network model is developed ~~in this report~~. Generic characteristics of the network information processing and transmission resources are identified as the basis for an evolutionary space communications network. Specific considerations for satellite data management algorithms are presented in terms of both mission-related and communications-related factors as well as relative performance measures. A comparative evaluation of data management algorithms is also given.

The final chapters of this report develop satellite network data management opportunities as well as identify specific areas requiring further technological development in the realization of an envisioned space-based information network. The concluding section presents recommendations for several study areas requiring additional investigation in support of this advanced communications network conceptual effort.

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